

Strange Quarks
Ohio University
May 12–13, 2000

Rare Kaon Decays

- Overview
- Lepton Flavor Violation
- CKM Matrix and CP Violation
 - $K_L^0 \rightarrow \pi^0 \ell^+ \ell^-$ and $K_L^0 \rightarrow \mu^+ \mu^-$
 - $K \rightarrow \pi \nu \bar{\nu}$
- Conclusions and Future Prospects

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Overview of Rare Kaon Decays

- **Forbidden Decays ($< 5 \times 10^{-12}$)**

- Probes of Lepton Flavor Violation

$$(\boxed{K_L^0 \rightarrow \mu e^-}, \boxed{K^+ \rightarrow \pi^+ \mu^+ e^-}, \boxed{K_L^0 \rightarrow \pi^0 \mu e^-})$$

- Forbidden in S.M.; allowed in some extensions

- Tremendous reach in mass scale ($\sim 100 \text{ TeV}/c^2$)

BNL: E871, E865; FNAL: E799-I \rightarrow KTeV

- **Rare Decays $O(10^{-10}-10^{-11})$**

- Suppressed in S.M. (FCNC)

- Clean measures of fundamental CKM parameters

$$(\boxed{K^+ \rightarrow \pi^+ \nu \bar{\nu}}, \boxed{K_L^0 \rightarrow \pi^0 \nu \bar{\nu}})$$

- Other measures ($\boxed{K_L^0 \rightarrow \pi^0 e^+ e^-}$, $\boxed{K_L^0 \rightarrow \mu^+ \mu^-}$)

BNL: E871, E787 \rightarrow E949; FNAL: CKM, KTeV \rightarrow KAMI;
KEK: E391a

- **other decays $O(10^{-9}-10^{-2})$**

- Testing ground for Chiral Perturbation Theory ($K^+ \rightarrow \pi^+ e^+ e^-$, $K \rightarrow \pi \gamma \gamma$, ...)

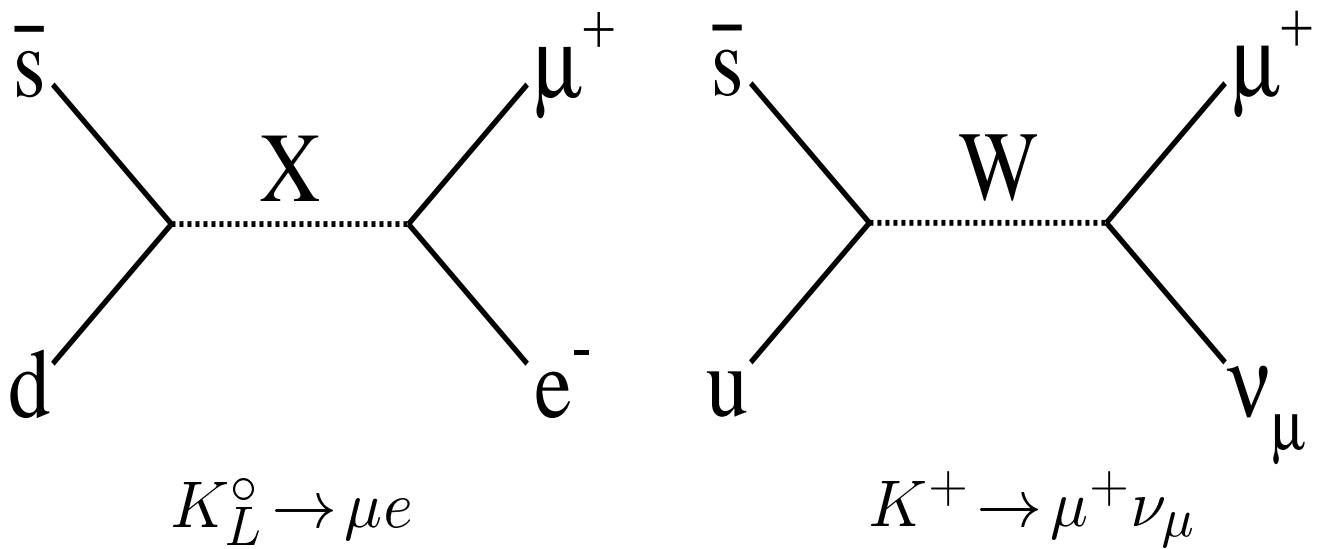
- S.M. Parameters ($K^+ \rightarrow \pi^0 e^+ \nu_e$)

BNL, CERN, FNAL, Frascati, IHEP, KEK

Lepton Flavor Violation (LFV)

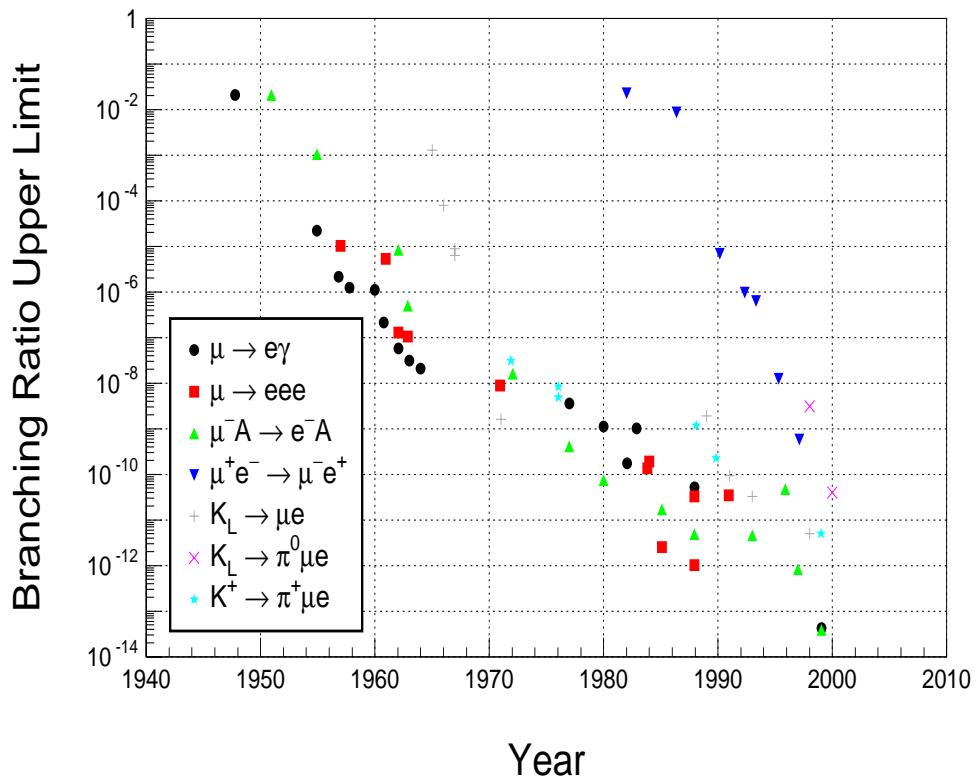
- There is good experimental evidence that there is an additive quantum number associated with each family of charged leptons.
- In the Standard Model there is no mechanism for violating lepton flavor (with $m_\nu = 0$); however, there is no underlying gauge symmetry that preserves lepton flavor.
- Non-zero m_ν produces LFV at rates too small to be observed in charge lepton decays.
- Observation of LFV would be unambiguous evidence for physics beyond the Standard Model.
- The mass scale probed by rare K decays is quite large:

$$M_X \simeq 200 \text{TeV}/c^2 \times \frac{g_X}{g} \times \left[\frac{10^{-12}}{\text{B}(K_L^\circ \rightarrow \mu e^-)} \right]^{1/4}$$



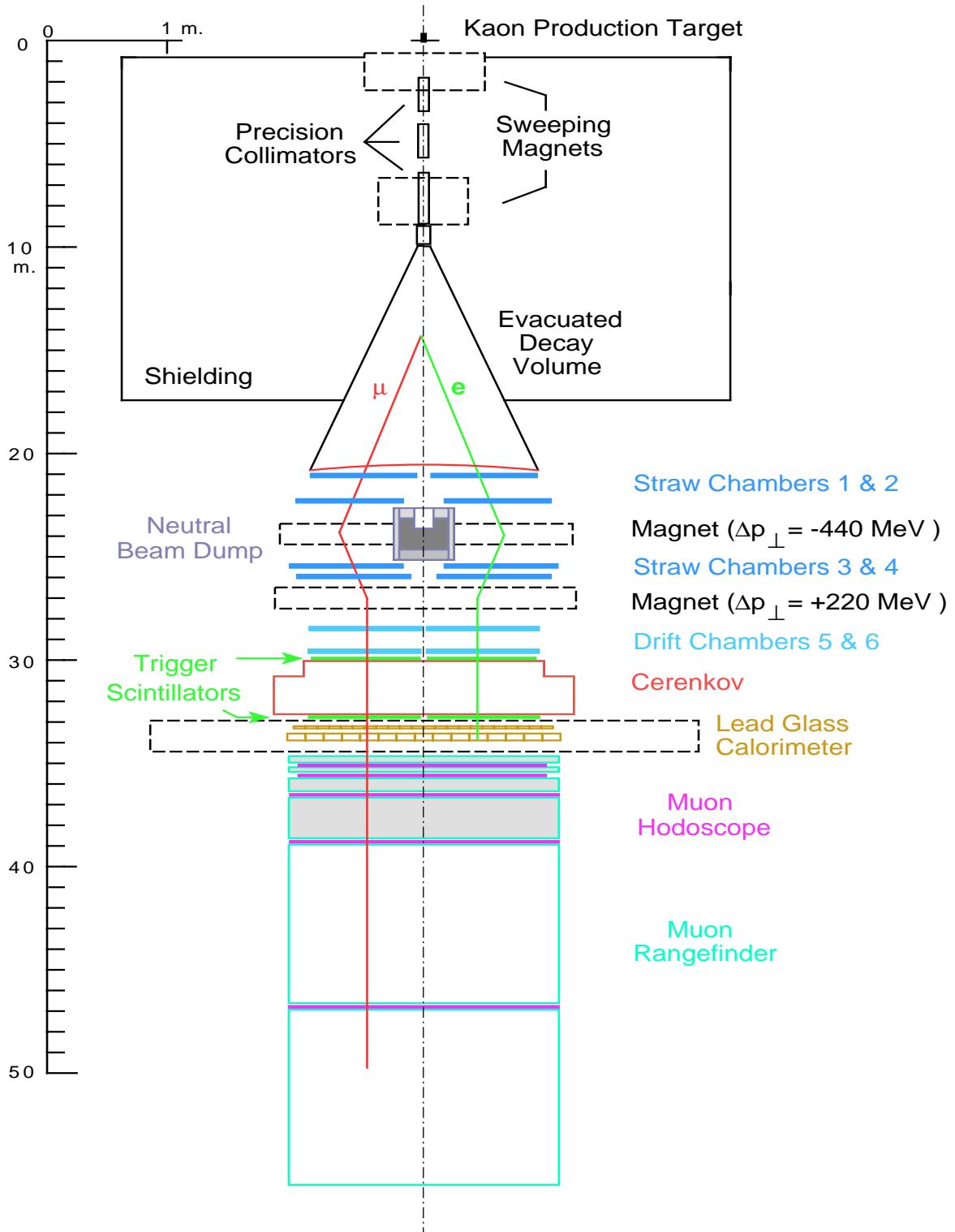
LFV

- rare K , μ , 0ν nuclear β , τ , B decays.
 - BNL E871: $K_L^0 \rightarrow \mu e$
 - BNL E865: $K^+ \rightarrow \pi^+ \mu^+ e^-$
 - FNAL E799: $K_L^0 \rightarrow \pi^0 \mu e$
- Rare kaon decays have achieved exquisite sensitivity and ruled out many extensions to the SM; however, it is considered to be difficult to push beyond $\mathcal{O}(10^{-13})$.
- The focus has shifted back to rare μ decays.



BNL E871: $K_L^0 \rightarrow \mu e$

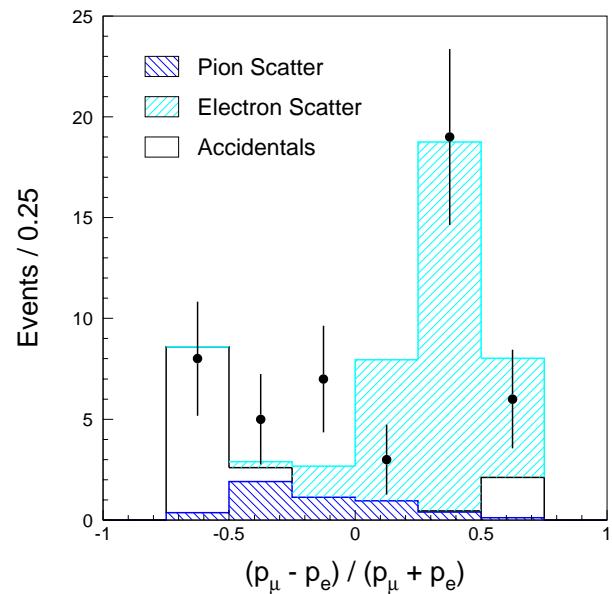
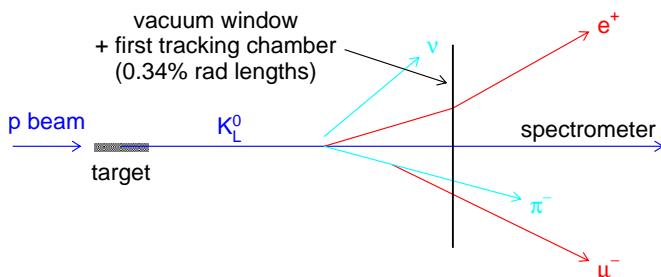
BNL Experiment 871 - The Search for $K_L^0 \rightarrow \mu e$



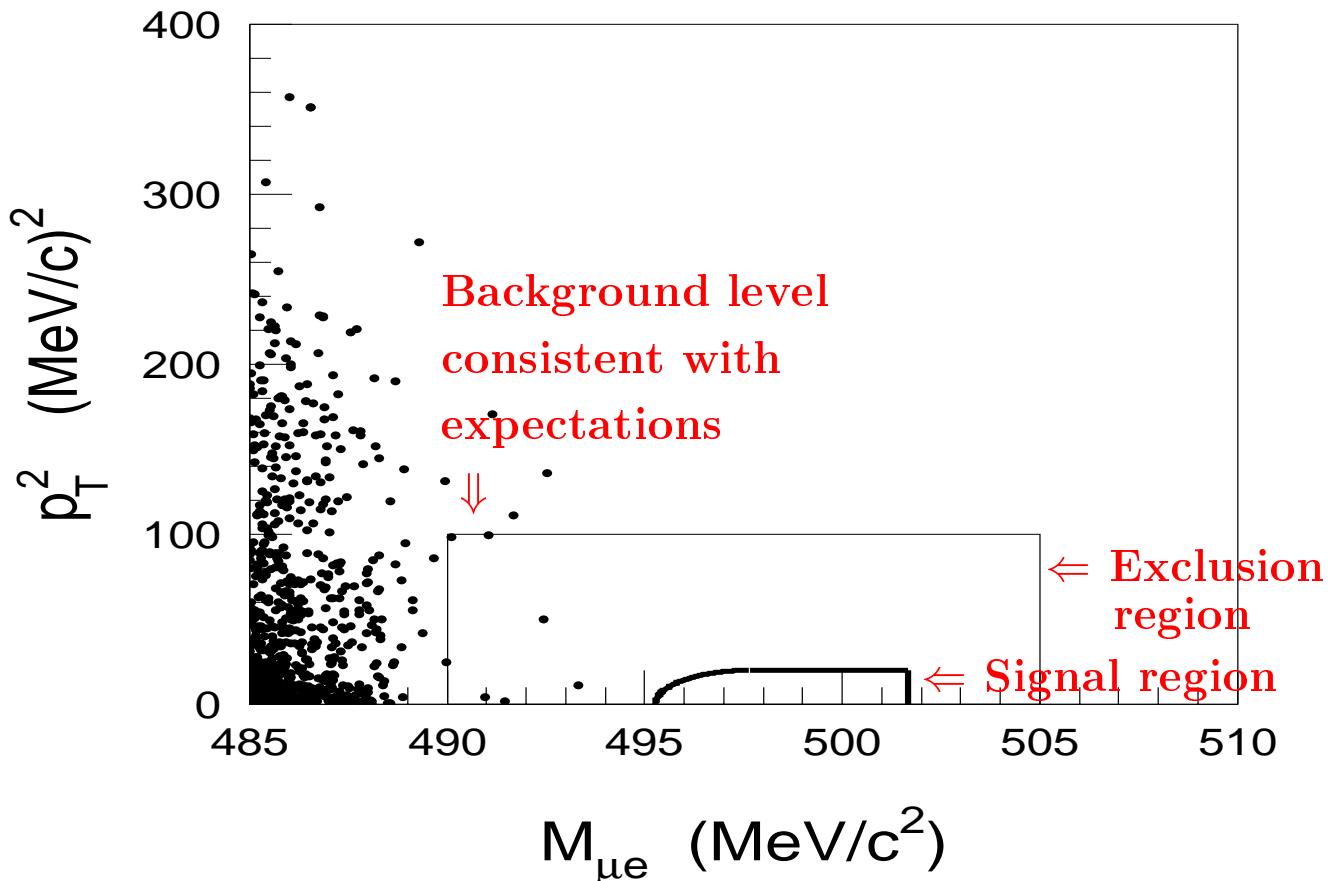
Irvine/Richmond/Standford/Texas/William and Mary

BNL E871: $K_L^0 \rightarrow \mu e$

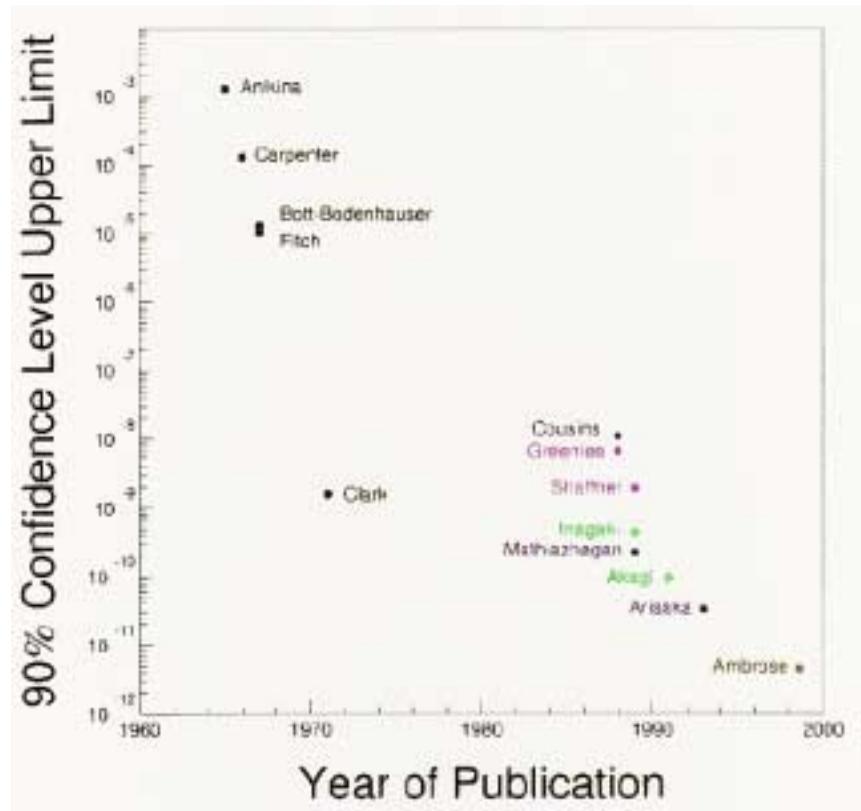
- Intense neutral beam — $K_L = 20$ MHz, neutrons ~ 3 GHz.
- Good kinematic resolution, redundant measurement ($\sigma_{M_{\pi\pi}} = 1.2$ MeV/c²).
- Redundant particle ID
- Beam plug reduces rate in particle ID detectors.
- Two-body kinematics exploited at first level trigger (require parallel tracks).
- Normalize to $K_L^0 \rightarrow \pi^+ \pi^-$
- Background dominated by $K_L^0 \rightarrow \pi^\pm e^\mp \nu_e$ with $\pi^+ \rightarrow \mu^+$ decay and a scattered electron in the vacuum window.



BNL E871: $K_L^0 \rightarrow \mu e$

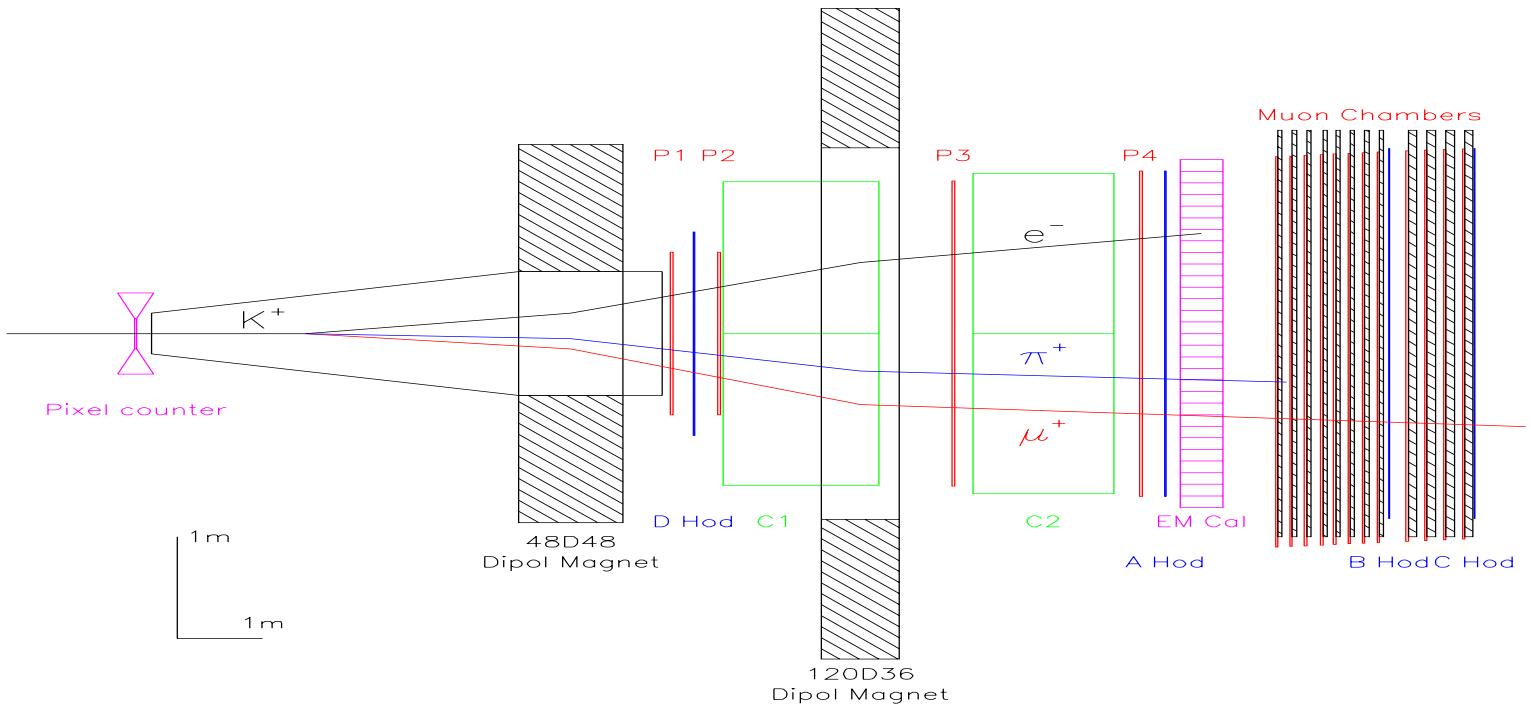


- No events in signal region, ~ 0.1 background.
- $B(K_L^0 \rightarrow \mu e) < 4.7 \times 10^{-12}$ [90% CL] (PRL **81**, 5734).
- No plans to push further (background at $\sim 10^{-13}$).



BNL E865: $K^+ \rightarrow \pi^+ \mu e$

E865, Plan Diagram, $K^+ \rightarrow \pi^+ \mu^+ e^-$



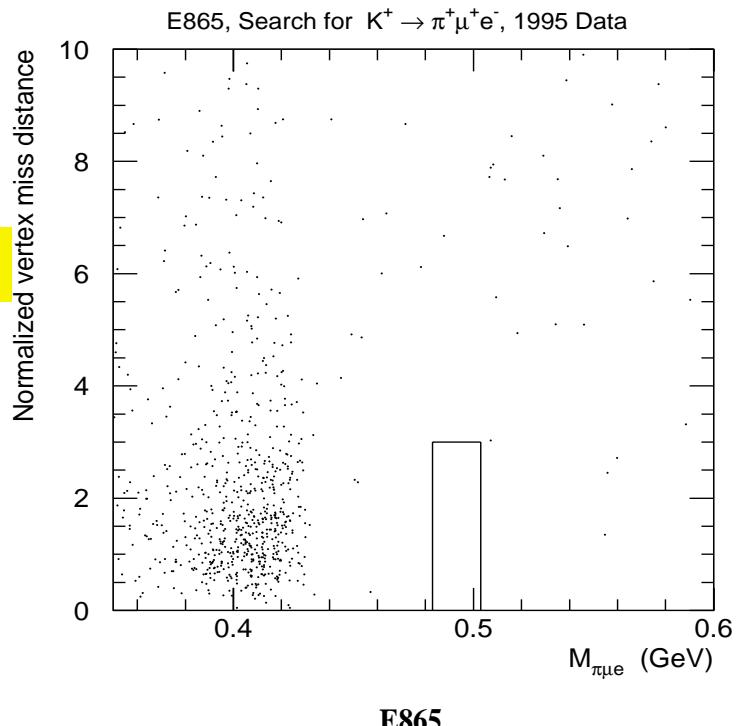
**Basel/BNL/INR/JINR/UNM/PSI
Pittsburg/Tbilisi/Yale/Zurich**

- 6 GeV/c unseparated K^+ beam (~ 50 MHz K^+)
- High rate detectors, redundant particle ID.
- Good vertex, from target, good track times, M_K
- Main background from accidentals.
- Normalize to $K^+ \rightarrow \pi^+ \pi^+ \pi^-$.
- Collected data from 1995–98.

BNL E865: $K^+ \rightarrow \pi^+ \mu^+ e^-$

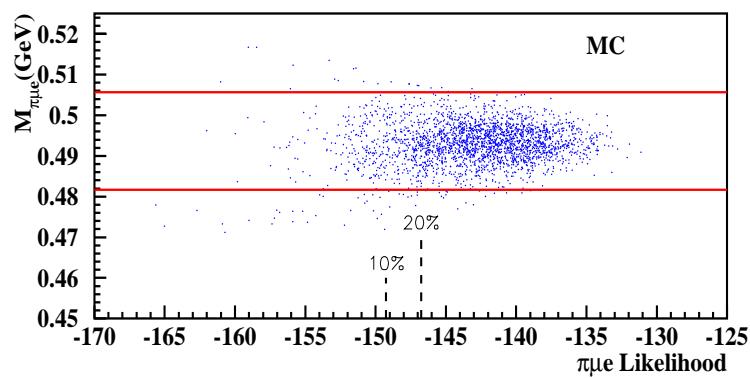
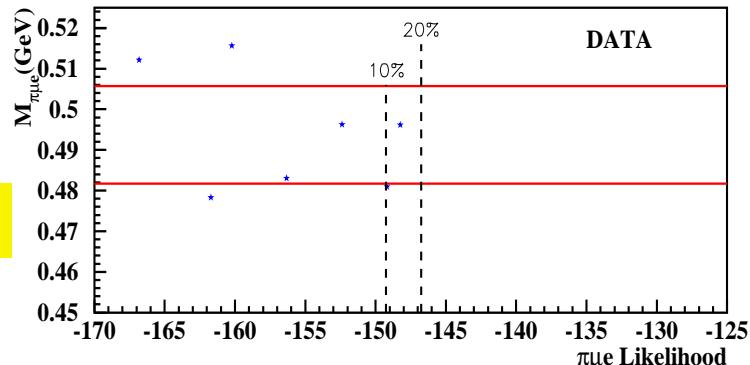
1995

- 1995 run was short.
- No events.
- $B(K^+ \rightarrow \pi^+ \mu^+ e^-) < 2.1 \times 10^{-10}$ (90% CL).



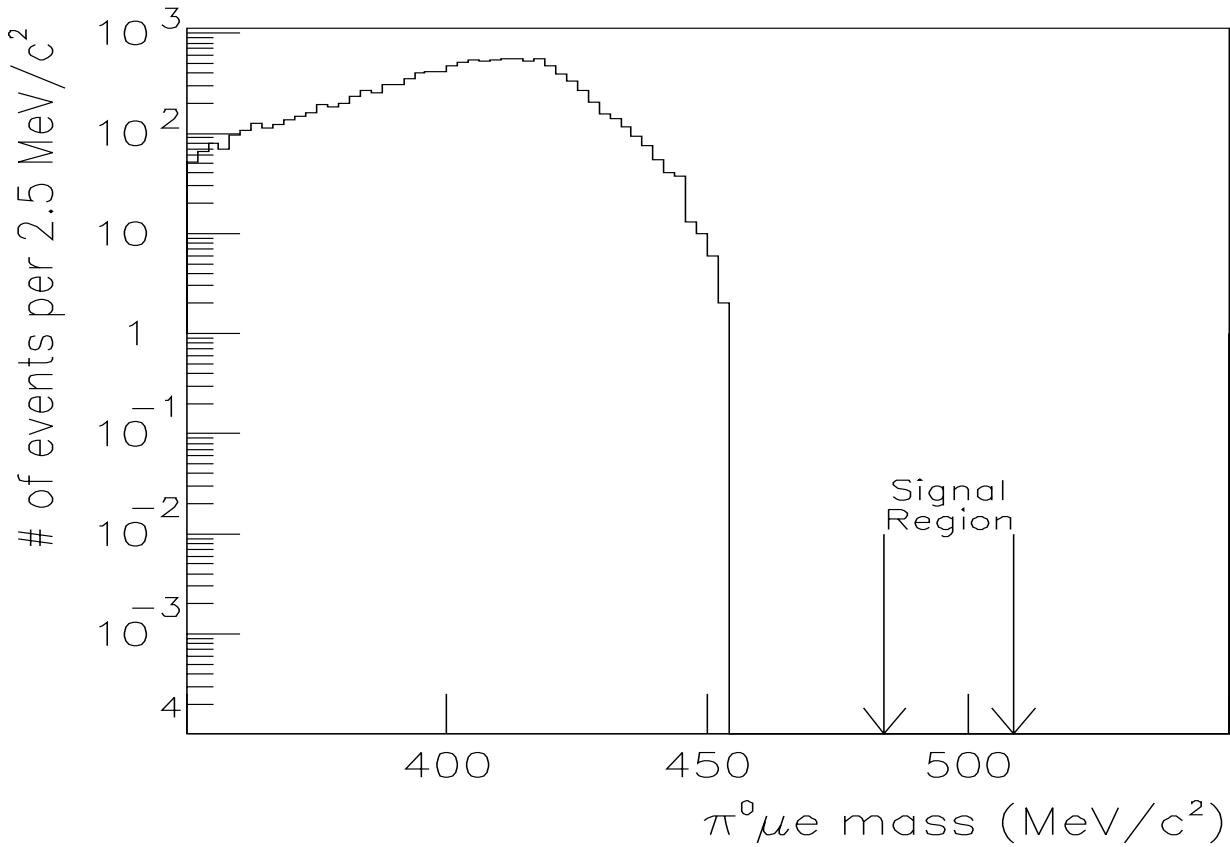
1996

- 1996 run was longer.
- No events with Likelihood $> 20\%$.
- $B(K^+ \rightarrow \pi^+ \mu^+ e^-) < 3.9 \times 10^{-11}$ (90% CL).



- 1997 run dedicated to $K^+ \rightarrow \pi^\circ e^+ \nu_e$, $K^+ \rightarrow \pi^+ \pi^- e^+ \nu_e$ and $K^+ \rightarrow \pi^+ \mu^+ \mu^-$.
- From E777 and E865: $B(K^+ \rightarrow \pi^+ \mu^+ e^-) < 2.8 \times 10^{-11}$ (90% CL)
- Expect $\sim \times 3$ more sensitivity from 1998 run.

FNAL E799-I: $K_L^0 \rightarrow \pi^0 \mu e$



- E799-I
- 3 EM clusters $E_{tot} > 55 \text{ GeV}$ (2 γ and 1 good e), 1 good μ .
- Kinematic cuts against $K_L^0 \rightarrow \pi^0 \pi^\pm \pi^\mp$ and $K_L^0 \rightarrow \pi^0 \pi^\pm e^\mp \nu$.
- Very small background level.
- $\mathbf{B(K_L^0 \rightarrow \pi^0 \nu \bar{\nu}) < 3.1 \times 10^{-9} \text{ (90\% CL)}}$ [PLB432,230 (1998)].
- Expect $>\times 10$ improvement from KTeV.

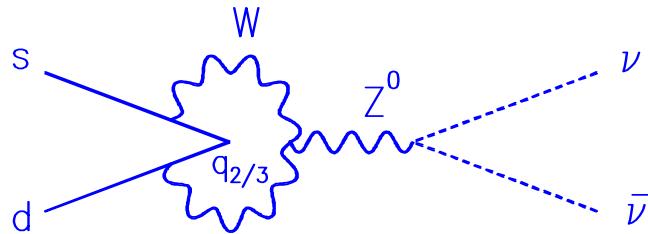
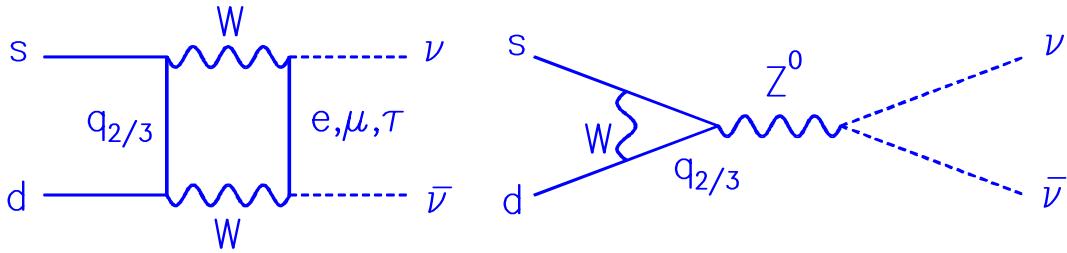
CKM Matrix and CP-Violation

$$V_{\text{CKM}} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \simeq \begin{pmatrix} 1 - \lambda^2/2 & \lambda & A\lambda^3(\bar{\rho} - i\bar{\eta}) \\ -\lambda & 1 - \lambda^2/2 & A\lambda^2 \\ A\lambda^3(1 - \bar{\rho} - i\bar{\eta}) & -A\lambda^2 & 1 \end{pmatrix}$$

$$\bar{\rho} = \rho(1 - \frac{\lambda^2}{2}) \quad \bar{\eta} = \eta(1 - \frac{\lambda^2}{2})$$

$K \rightarrow \pi \nu \bar{\nu}$: The Golden Modes

- $K^+ \rightarrow \pi^+ \nu \bar{\nu}$: measure $|\lambda_t| \equiv |V_{ts}^* V_{td}|$.
- $K_L^\circ \rightarrow \pi^\circ \nu \bar{\nu}$: direct CP violating, measure $\text{Im}(\lambda_t) = \text{Im}(V_{ts}^* V_{td})$. This is the best way to measure $\text{Im}(\lambda_t)$ and the Jarlskog invariant J_{CP} .

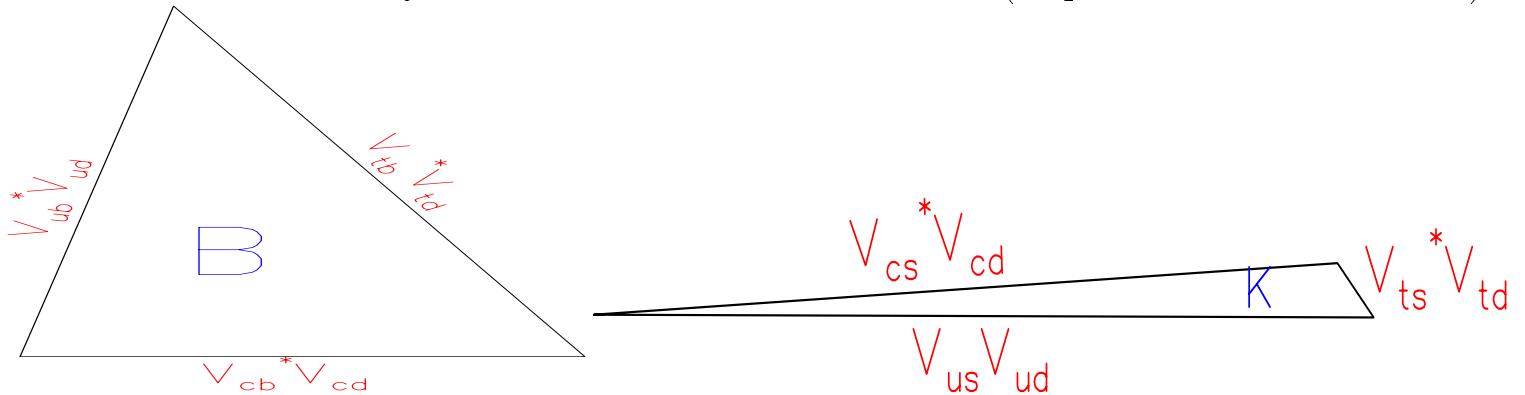


Two other modes from which CKM parameters may be extracted:

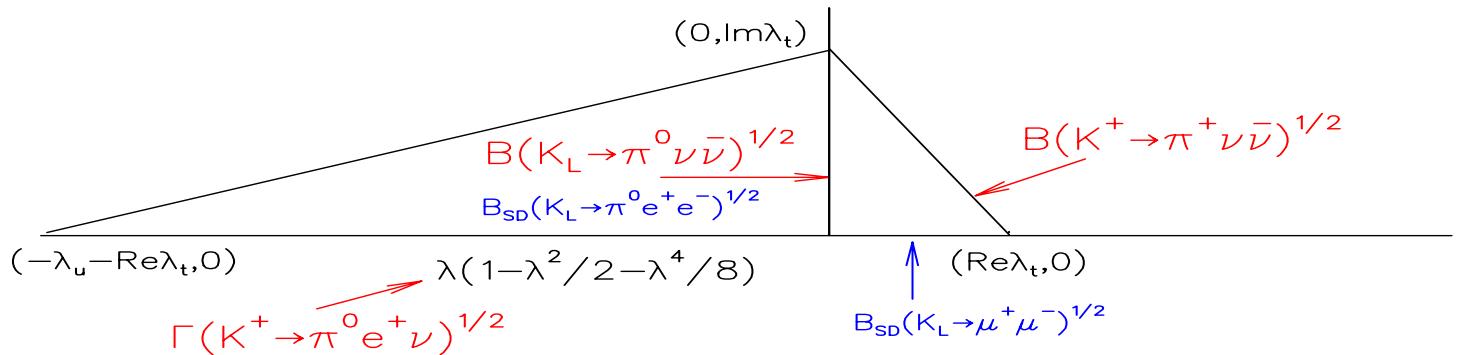
- $\text{BR}_{SD}(K_L^\circ \rightarrow \mu^+ \mu^-)$: measure $\text{Re}(V_{ts}^* V_{td})$. Need to extract long distance dispersive part ($K_L^\circ \rightarrow e^+ e^- \gamma$, $K_L^\circ \rightarrow \mu^+ \mu^- \gamma$, $K_L^\circ \rightarrow e^+ e^- e^+ e^-$, $K_L^\circ \rightarrow \mu^+ \mu^- e^+ e^-$ and ChPT)
- $\text{BR}_{SD}(K_L^\circ \rightarrow \pi^\circ e^+ e^-)$: direct CP-violating component. Need to extract CP conserving ($K_L^\circ \rightarrow \pi^\circ \gamma \gamma$ and ChPT) and indirect CP-violating components ($K_S^\circ \rightarrow \pi^\circ e^+ e^-$).

Rare Kaon Decays and the CKM Matrix

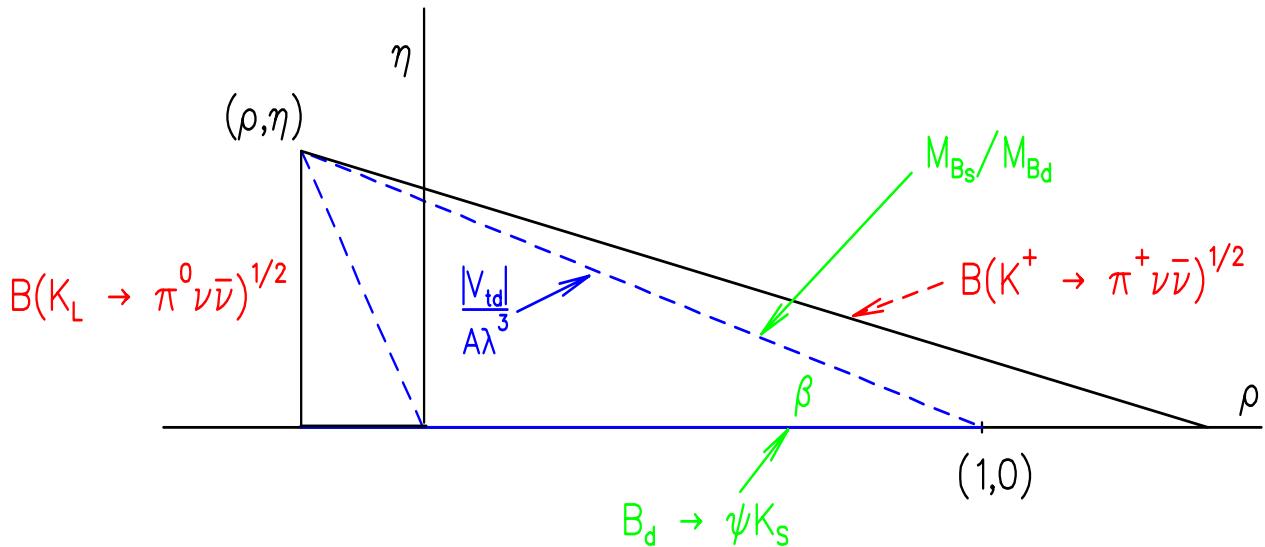
There are six unitarity relations: all should be tested (requires 3 measurements).



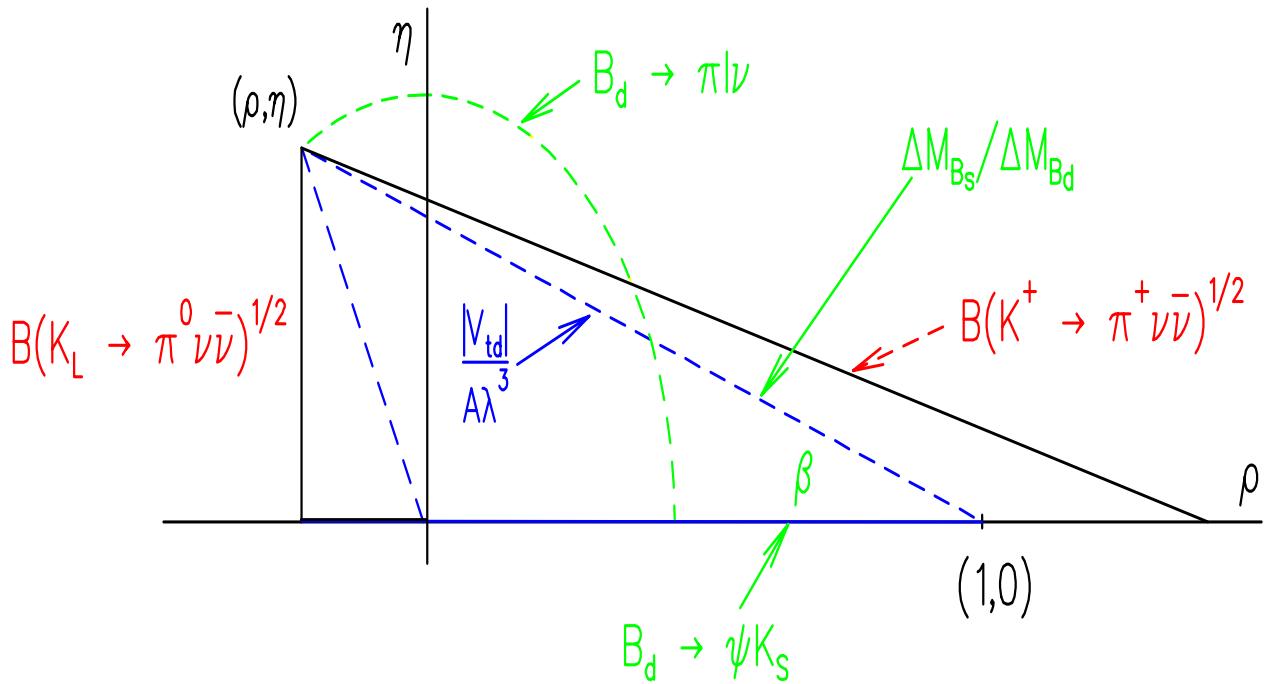
The fundamental measure of CP violation, J_{CP} is related to the area of the triangle and should be measured as well as possible (in as many ways as possible). In the kaon triangle, only two measurements are needed to determine the area: $K^+ \rightarrow \pi^0 e^+ \nu_e$ and $K_L^0 \rightarrow \pi^0 \nu \bar{\nu}$; and we can completely determine the unitarity triangle with theoretically unambiguous measurements::



Using only those modes with little or no theoretical ambiguity there are 4 constraints on the two variables (in the conventional representation of the triangle):



$K \rightarrow \pi \nu \bar{\nu}$



From our current knowledge of the CKM parameters we obtain

$K^+ \rightarrow \pi^+ \nu \bar{\nu}$:

$$\begin{aligned}
 B(K^+ \rightarrow \pi^+ \nu \bar{\nu}) &= \frac{\kappa_+ \alpha^2 B(K^+ \rightarrow \pi^\circ e^+ \nu_e)}{2\pi^2 \sin^4 \theta_W |V_{us}|^2} \sum_l |X_t V_{ts}^* V_{td} + X_c V_{cs}^* V_{cd}|^2 \\
 &= 8.88 \times 10^{-11} A^4 [(\bar{\rho}_0 - \bar{\rho})^2 + (\sigma \bar{\eta})^2] \\
 &= (0.82 \pm 0.32) \times 10^{-10}
 \end{aligned}$$

There is also a relation, free of theoretical ambiguity, between $\frac{\Delta M_{Bs}}{\Delta M_{Bd}}$ and $K^+ \rightarrow \pi^+ \nu \bar{\nu}$:

$$B(K^+ \rightarrow \pi^+ \nu \bar{\nu}) < 0.4 \times 10^{-10} \left[P_{charm} + A^2 X(x_t) \frac{r_{sd}}{\lambda} \sqrt{\frac{\Delta M_d}{\Delta M_s}} \right]^2 \text{ with } r_{sd} = \frac{f_{B_s} \sqrt{B_{B_s}}}{f_{B_d} \sqrt{B_{B_d}}} < 1.4$$

$$B(K^+ \rightarrow \pi^+ \nu \bar{\nu}) < 1.67 \times 10^{-10}$$

$K_L^\circ \rightarrow \pi^\circ \nu \bar{\nu}$:

$$\begin{aligned}
 B(K_L^\circ \rightarrow \pi^\circ \nu \bar{\nu}) &= \frac{\tau_{K_L}}{\tau_{K^+}} \frac{\kappa_L \alpha^2 B(K_{e3})}{2\pi^2 \sin^4 \theta_W |V_{us}|^2} \sum_l |Im(V_{ts}^* V_{td}) X_t|^2 \\
 &= 4.08 \times 10^{-10} A^4 \eta^2 = 1.56 \times 10^{-4} [Im(V_{ts}^* V_{td})]^2 \\
 &= (3.1 \pm 1.1) \times 10^{-11}
 \end{aligned}$$

CKM Measurements from the Kaon System

Modes with Theoretical ambiguities:

- $K_L^\circ \rightarrow \mu^+ \mu^-$: BNL E871
- $K_L^\circ \rightarrow \pi^\circ e^+ e^-$, $K_L^\circ \rightarrow \pi^\circ \mu^+ \mu^-$: KTeV
- ϵ'/ϵ : KTeV, NA48, KLOE

Golden Modes:

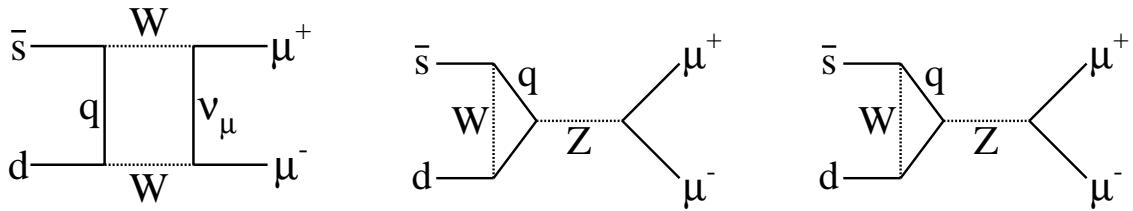
- KTeV: $K_L^\circ \rightarrow \pi^\circ \nu \bar{\nu}$
- E787: $K^+ \rightarrow \pi^+ \nu \bar{\nu}$

Future Prospects

- $K^+ \rightarrow \pi^+ \nu \bar{\nu}$: BNL E949, FNAL CKM
- $K_L^\circ \rightarrow \pi^\circ \nu \bar{\nu}$: KEK E391a, BNL KOPIO, FNAL KAMI

$$\underline{K_L^{\circ} \rightarrow \mu^+ \mu^- \text{ and } K_L^{\circ} \rightarrow \pi^{\circ} \ell^+ \ell^-}$$

$$\underline{K_L^{\circ} \rightarrow \mu^+ \mu^-}$$

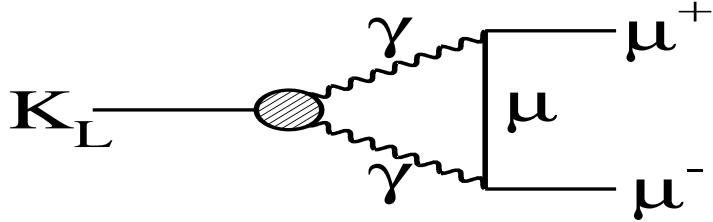


Short distance contribution is dominated by internal top quark loops and is sensitive to $Re(\lambda_t) = Re(V_{ts}^* V_{td})$ or equivalently to ρ .

$$\begin{aligned} B_{SD}(K_L^{\circ} \rightarrow \mu^+ \mu^-) &= \frac{\tau_L}{\tau_{K^+}} \frac{\alpha^2 B(K_{\mu 2})}{\pi^2 \sin^4 \theta_W |V_{us}|^2} [Y_c Re(\lambda_c) + Y_t Re(\lambda_t)]^2 \\ &= 1.51 \times 10^{-9} A^4 (\rho_0 - \bar{\rho})^2 \\ &\simeq 7 \times 10^{-10} \end{aligned}$$

BUT

The decay is dominated by $K_L^{\circ} \rightarrow \gamma\gamma$ ($\gamma\gamma \rightarrow \mu^+ \mu^-$):



From the measured $B(K_L^{\circ} \rightarrow \gamma\gamma) = (5.92 \pm 0.15) \times 10^{-4}$ and the QED calculation we have $B_{abs}(K_L^{\circ} \rightarrow \mu^+ \mu^-) = (7.07 \pm 0.18) \times 10^{-9}$.

BUT

there is also a long distance contribution from two off-shell photons that can interfere with the short distance contribution. Calculation of this contribution is controversial and needs ChPT and measurements of $K_L^{\circ} \rightarrow e^+ e^- \gamma$, $K_L^{\circ} \rightarrow \mu^+ \mu^- \gamma$, $K_L^{\circ} \rightarrow \mu^+ \mu^- e^+ e^-$, $K_L^{\circ} \rightarrow e^+ e^- e^+ e^-$

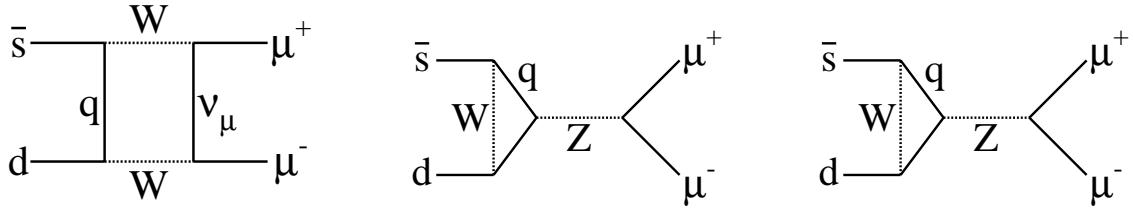
$$\underline{K_L^{\circ} \rightarrow \pi^{\circ} e^+ e^- , K_L^{\circ} \rightarrow \pi^{\circ} \mu^+ \mu^-}$$

Short distance contribution direct CP violating and is dominated by internal top quark loops and is sensitive to $Im(\lambda_t) = Im(V_{ts}^* V_{td})$ or equivalently to η .

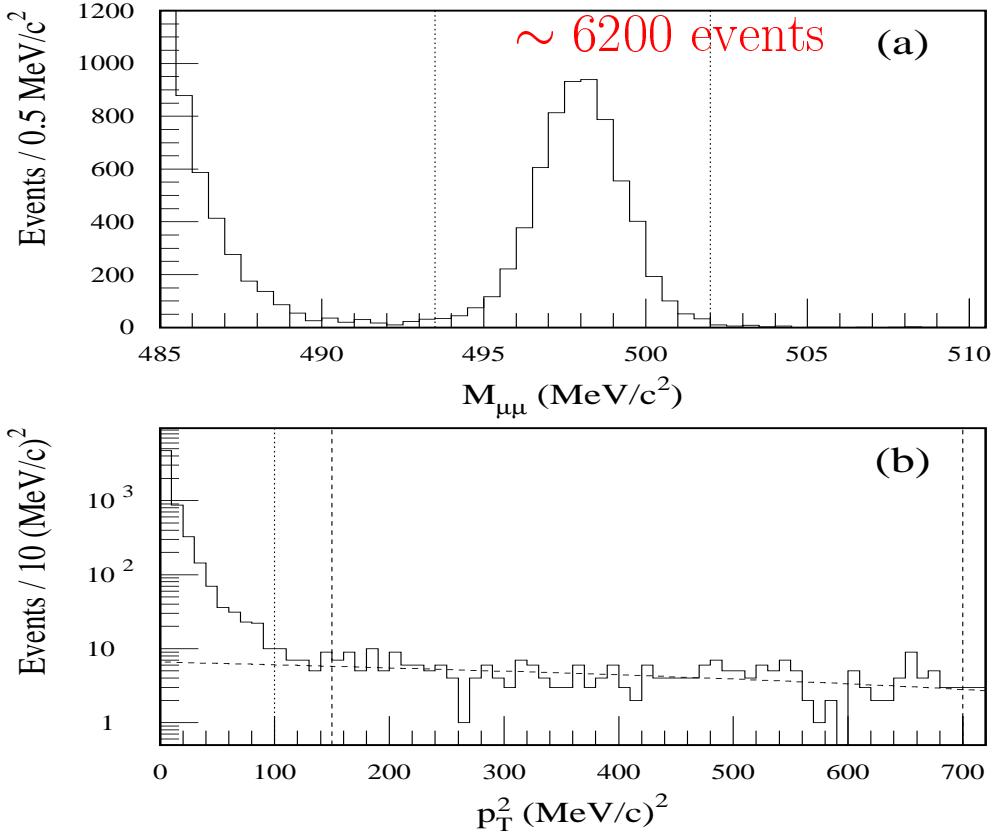
$$\begin{aligned} B_{SD}(K_L^{\circ} \rightarrow \pi^{\circ} e^+ e^-) &= \frac{\kappa_L \tau_L \alpha^2 B(K_{e3})}{\tau_{K^+} 4 \pi^2 |V_{us}|^2} (y_{7A}^2 + y_{7V}^2) |Im(\lambda_t)|^2 \\ &= 6.91 \times 10^{-11} A^4 \eta^2 \\ &\simeq 5 \times 10^{-12} \end{aligned}$$

Due to reduced phase space, $B(K_L^{\circ} \rightarrow \pi^{\circ} \mu^+ \mu^-)$ is suppressed by a factor of five.

BNL E871: $K_L^\circ \rightarrow \mu^+ \mu^-$



$$B_{SD}(K_L^\circ \rightarrow \mu^+ \mu^-) = 0.41 \times 10^{-9} A^4 |C_\mu(x_t)|^2 (1 - \rho)^2$$



$$B(K_L^\circ \rightarrow \mu^+ \mu^-) = (7.18 \pm 0.17) \times 10^{-9}$$

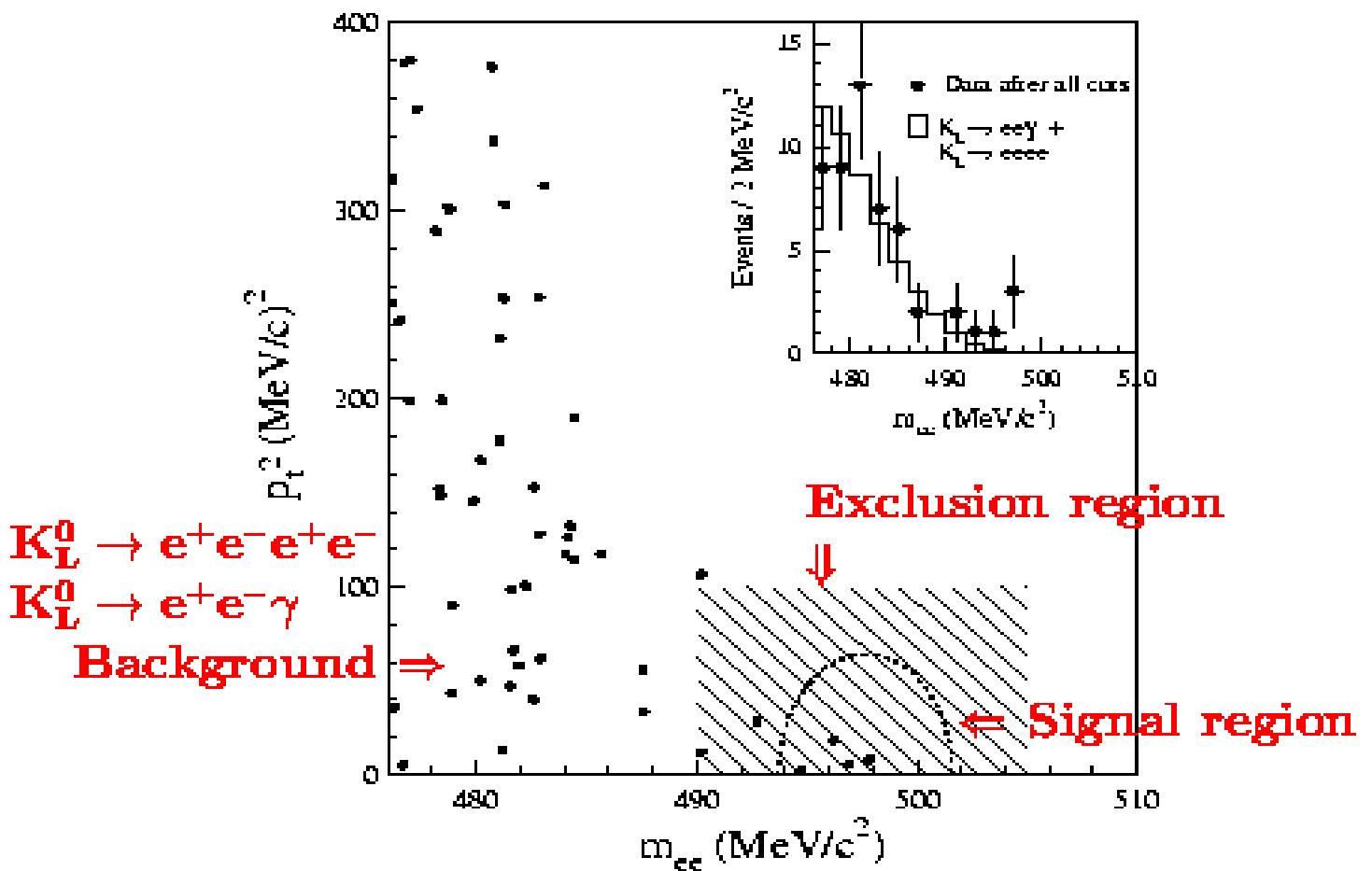
$$\begin{aligned} \frac{\Gamma(K_L^\circ \rightarrow \mu^+ \mu^-)}{\Gamma(K_L^\circ \rightarrow \gamma\gamma)} &= \left[\frac{B(K_L^\circ \rightarrow \mu^+ \mu^-)}{B(K_L^\circ \rightarrow \pi^+ \pi^-)} \right] \times \left[\left| \frac{\eta_{+-}}{\eta_{\infty}} \right| \times \frac{B(K_S^\circ \rightarrow \pi^+ \pi^-)}{B(K_S^\circ \rightarrow \pi^+ \pi^-)} \right] \times \left[\frac{B(K_L^\circ \rightarrow \pi^+ \pi^-)}{B(K_L^\circ \rightarrow \gamma\gamma)} \right] \\ &[(3.474 \pm .054) \times 10^{-6}] [(1.0044 \pm 0.0023)(2.186 \pm 0.028)] [0.632 \pm 0.009] \\ &[1.55\%][(0.23\%)(1.28\%)][1.42\%] \\ &= (1.213 \pm 0.030) \times 10^{-5} [2.48\%] \end{aligned}$$

$$\text{Unitarity bound} = (1.20) \times 10^{-5}$$

Subtracting off the contribution from 2 real photons and correcting for the contribution from 2 off-shell photons, a limit on the short distance contribution gives:

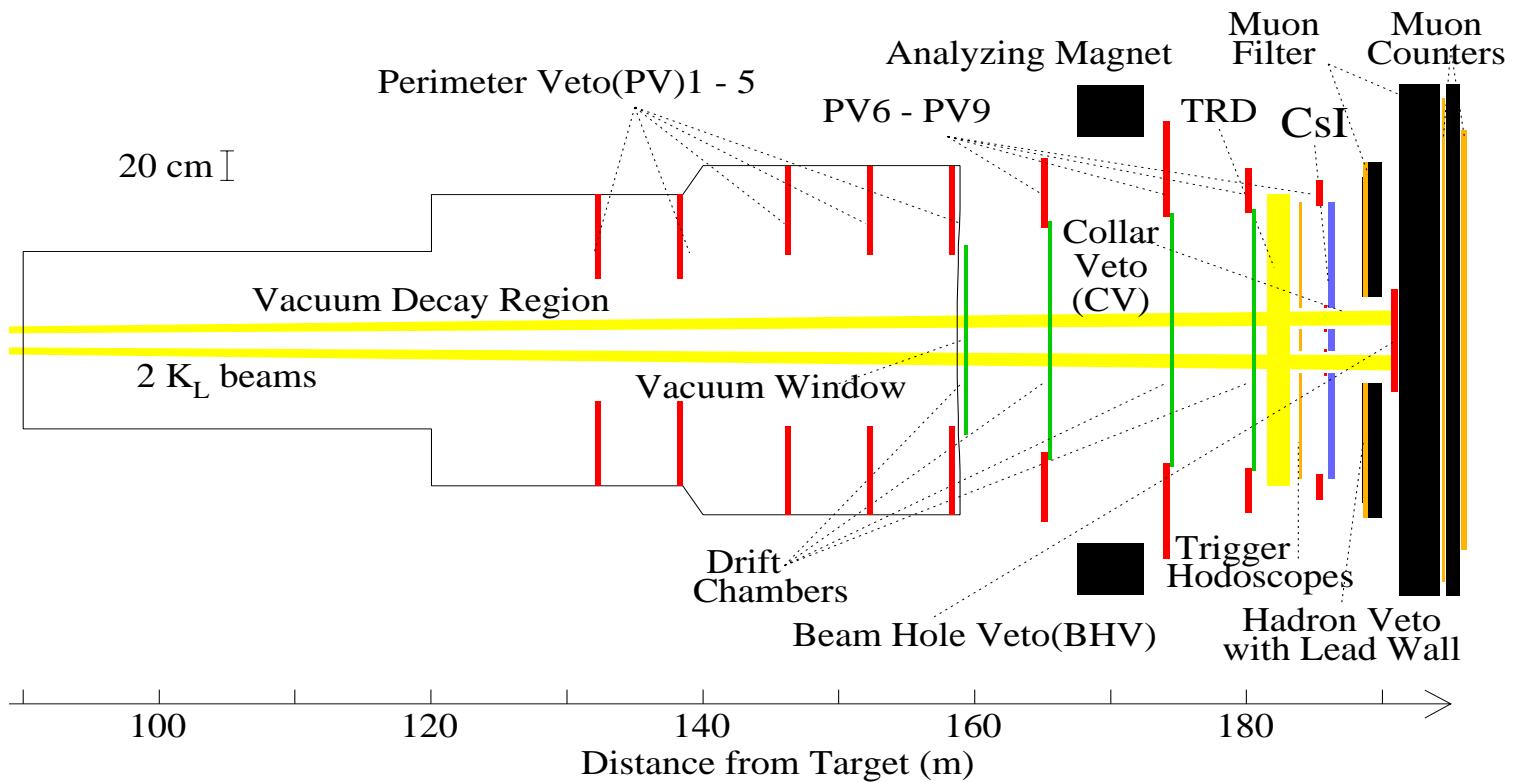
$$\rho > -0.29 \text{ (90\% CL)}$$

BNL E871: $K_L^0 \rightarrow e^+e^-$



- Cuts tuned without looking in exclusion region.
- 4 events in signal region, with ~ 0.2 background.
- $B(K_L^0 \rightarrow e^+e^-) = (8.7^{+5.7}_{-4.1}) \times 10^{-12}$ (PRL **81**, 4309).
- $B(K_L^0 \rightarrow e^+e^-)$ consistent with ChPT $[(9.0 \pm 0.5) \times 10^{-12}]$.
- Smallest branching ratio ever measured.

KTeV (FNAL E799): $K_L^0 \rightarrow \pi^0 e^+ e^-$

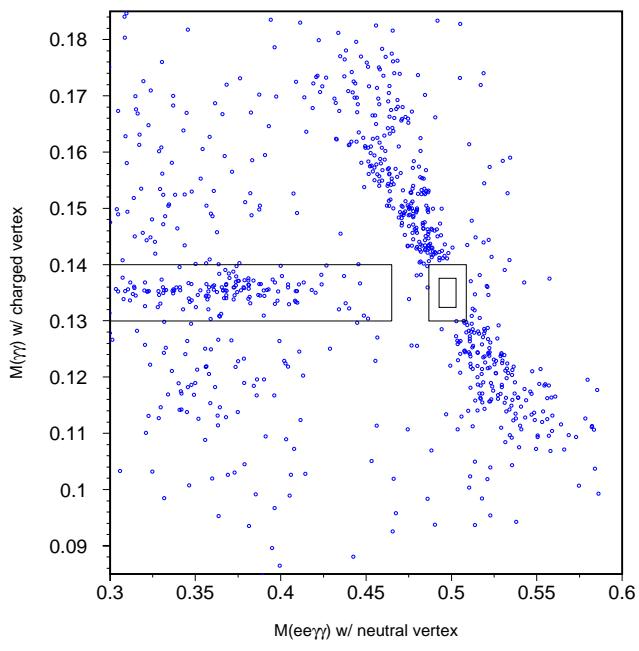


Arizona/Chicago/Colorado/Elmhurst/FNAL/Osaka
Rice, Rutgers, UCLA, UCSD, Virginia, Wisconsin

- Very good CsI calorimeter ($\sigma_E/E = 1\% @ 15 \text{ GeV}$).
- TRD: π/e rejection of ~ 400 ($\epsilon_e = 0.9$).
- High intensity, well collimated K_L beam.
- Runs in 1996–7 and 1999–2000.

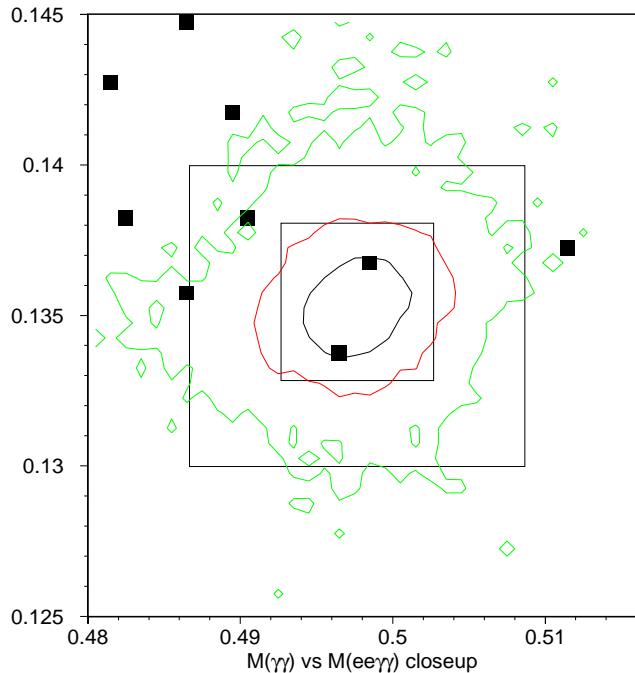
FNAL KTeV: $K_L^0 \rightarrow \pi^0 e^+ e^-$

Box excluded



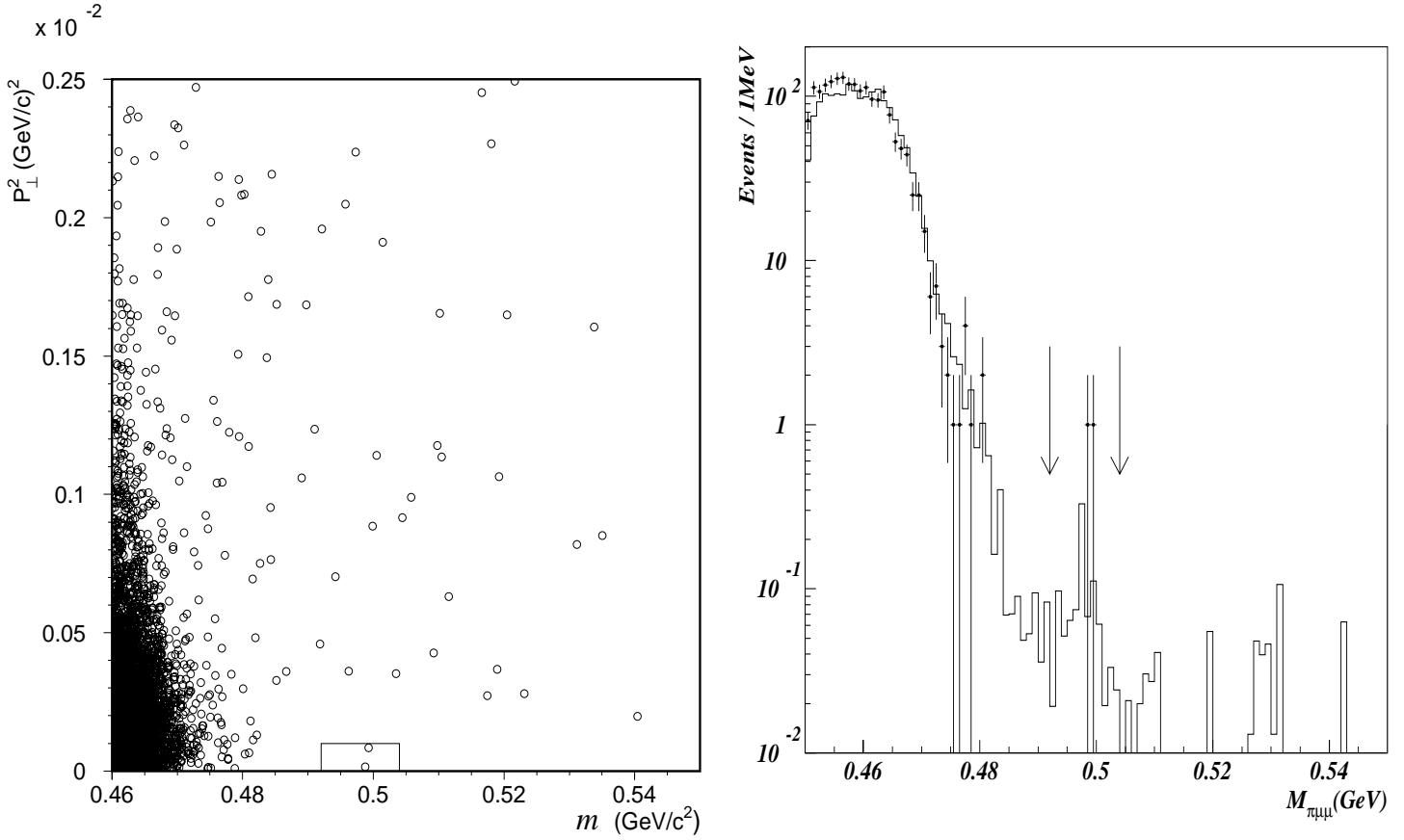
Expanded View

99/03/08 09.22



- Expected background 1.5 ± 0.4 , mostly $K_L^0 \rightarrow e^+ e^- \gamma\gamma$.
- 2 events observed, consistent with background.
- $B(K_L^0 \rightarrow \pi^0 e^+ e^-) < 5.6 \times 10^{-10}$ [90% CL] (Moriond99)
- 1997–99 data should improve limit by $\times 2$

FNAL KTeV: $K_L^0 \rightarrow \pi^0 \mu^+ \mu^-$



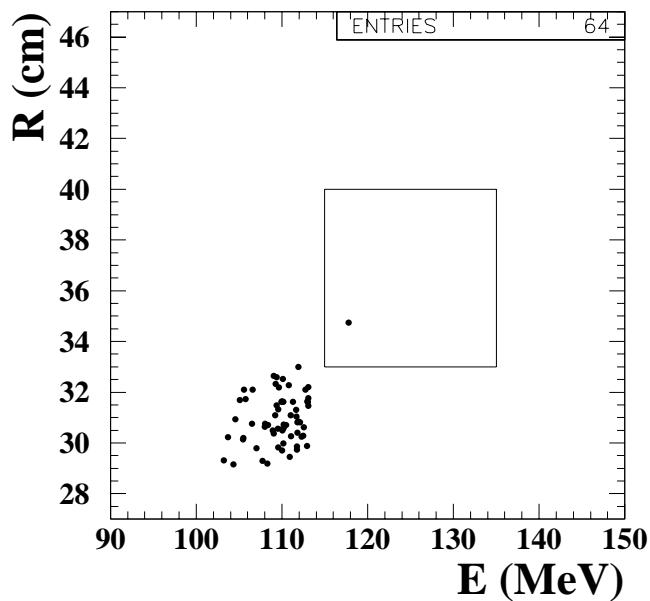
- Expected background 0.9 ± 0.2 .
- 2 events observed, consistent with background.
- $\mathcal{B}(K_L^0 \rightarrow \pi^0 e^+ e^-) < 3.8 \times 10^{-10}$ [90% CL] ([hep/ex-0001006](#))
- 1997–99 data should improve limit by $\times 2$

Other ‘Rare’ Kaon Decays

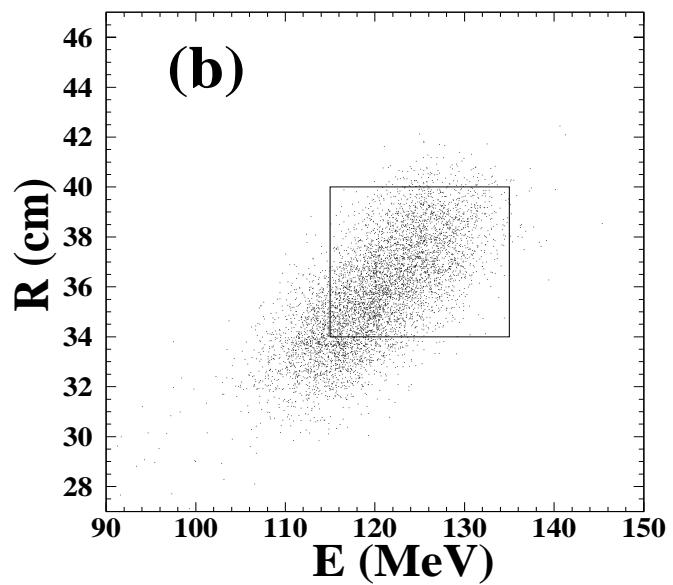
Decay Mode	Branching Ratio	events	Experiment
K_{γγ}			
$K_S^0 \rightarrow \gamma\gamma$	$(2.4 \pm 0.9) \times 10^{-6}$	16	NA31-95
$K_L^0 \rightarrow \gamma\gamma$	$(5.92 \pm 0.15) \times 10^{-4}$	110000	NA31-87
$K_L^0 \rightarrow e^+e^-\gamma$	$(1.06 \pm 0.02 \pm 0.02 \pm 0.04) \times 10^{-5}$	6854	NA48-99
$K_L^0 \rightarrow \mu^+\mu^-\gamma$	$(3.69 \pm 0.04 \pm 0.07) \times 10^{-7}$	9105	KTeV-00
$K_L^0 \rightarrow e^+e^-e^+e^-$	$(4.14 \pm 0.27 \pm 0.31) \times 10^{-8}$	300	KTeV-98
$K_L^0 \rightarrow \mu^+\mu^-e^+e^-$	—	~40	KTeV-99
$K_S^0 \rightarrow \mu^+\mu^-$	$< 3.2 \times 10^{-7}$	0	CERN-73
$K_S^0 \rightarrow e^+e^-$	$< 1.4 \times 10^{-7}$	0	CLEAR-97
$K_L^0 \rightarrow e^+e^-\gamma\gamma$	$(6.31 \pm 0.14 \pm 0.42) \times 10^{-7}$	1911	KTeV-00
$K_L^0 \rightarrow \mu^+\mu^-\gamma\gamma$	$(1.42^{+1.02}_{-0.81} \pm 0.14) \times 10^{-9}$	4	KTeV-00
K_{πγγ}			
$K_L^0 \rightarrow \pi^0\gamma\gamma$	$(1.68 \pm 0.07 \pm 0.08) \times 10^{-6}$	884	KTeV-99
$K^+ \rightarrow \pi^+\gamma\gamma$	$(6.0 \pm 1.5 \pm 0.7) \times 10^{-7}$	26	E787-97
$K_L^0 \rightarrow \pi^0e^+e^-\gamma$	$(2.20 \pm 0.48 \pm 0.11) \times 10^{-8}$	18	KTeV-99
$K^+ \rightarrow \pi^+e^+e^-$	$(2.94 \pm 0.05 \pm 0.13) \times 10^{-7}$	10300	E865-99
$K^+ \rightarrow \pi^+\mu^+\mu^-$	$(9.22 \pm 0.60 \pm 0.49) \times 10^{-8}$	430	E865-00
$K^+ \rightarrow \pi^+e^+e^-\gamma$	—	~30	E865-99
$K_L^0 \rightarrow \pi^0e^+e^-\gamma$	$(2.20 \pm 0.48 \pm 0.11) \times 10^{-8}$	18	KTeV-99
K_{ππγ}			
$K_L^0 \rightarrow \pi^+\pi^-\gamma$ (DE)	$(3.70 \pm 0.10) \times 10^{-5}$	5900	KTeV-00
$K^+ \rightarrow \pi^+\pi^0\gamma$ (DE)	$(4.72 \pm 0.77) \times 10^{-6}$	360	E787-00
$K_L^0 \rightarrow \pi^+\pi^-e^+e^-$	$(3.63 \pm 0.11 \pm 0.14) \times 10^{-7}$	1500	KTeV-98
$K_S^0 \rightarrow \pi^+\pi^-e^+e^-$	4×10^{-5}	58	NA48-00
$K_L^0 \rightarrow \pi^0\pi^0\gamma$	$< 5.6 \times 10^{-6}$	0	NA31-94
$K_S^0 \rightarrow \pi^+\pi^-\gamma$	$(1.78 \pm 0.05) \times 10^{-3}$	3700	E731-93
$K_S^0 \rightarrow \pi^+\pi^-\gamma$ (DE)	$< 0.06 \times 10^{-3}$	0	CERN-76
K_{ℓνℓ'ℓ'}			
$K^+ \rightarrow \mu^+\nu_\mu\gamma$	$(5.50 \pm 0.28) \times 10^{-3}$		KEK-85
$K^+ \rightarrow \mu^+\nu_\mu\gamma$ (DE)	$(1.33 \pm 0.12 \pm 0.18) \times 10^{-5}$	2588	E787-00
$K^+ \rightarrow e^+\nu_\mu\gamma$ (DE)	$(1.52 \pm 0.23) \times 10^{-5}$	51	CERN-79
$K^+ \rightarrow \mu^+\nu\mu^+\mu^-$	$< 4.1 \times 10^{-7}$	0	E787-89
$K^+ \rightarrow e^+\nu\mu^+\mu^-$	$< 5.0 \times 10^{-7}$	0	E787-98
$K^+ \rightarrow \mu^+\nu e^+e^-$	$6.84 \pm 0.40 \times 10^{-8}$	~1500	E865-00
$K^+ \rightarrow e^+\nu e^+e^-$	$2.60 \pm 0.15 \times 10^{-8}$	~400	E865-00
Selected other other			
$K^+ \rightarrow \pi^+\pi^-e^+\nu_e$	—	> 350000	E865-00
$K^+ \rightarrow \pi^+\pi^-e^+\nu_e\gamma$	—		E865-00
$K_S^0 \rightarrow \pi^0\pi^+\pi^-$	$(2.5^{+1.3}_{-1.0}{}^{+0.5}_{-0.6}) \times 10^{-7}$		CLEAR-97
$K_S^0 \rightarrow \pi^0\pi^0\pi^0$	$< 1.4 \times 10^{-5}$	0	SND-99
$K_L^0 \rightarrow \pi^\pm\mu^\mp\nu_\mu\gamma$	$(5.7^{+0.6}_{-0.7}) \times 10^{-4}$	252	NA48-98

$K^+ \rightarrow \pi^+ \nu \bar{\nu}$ Event

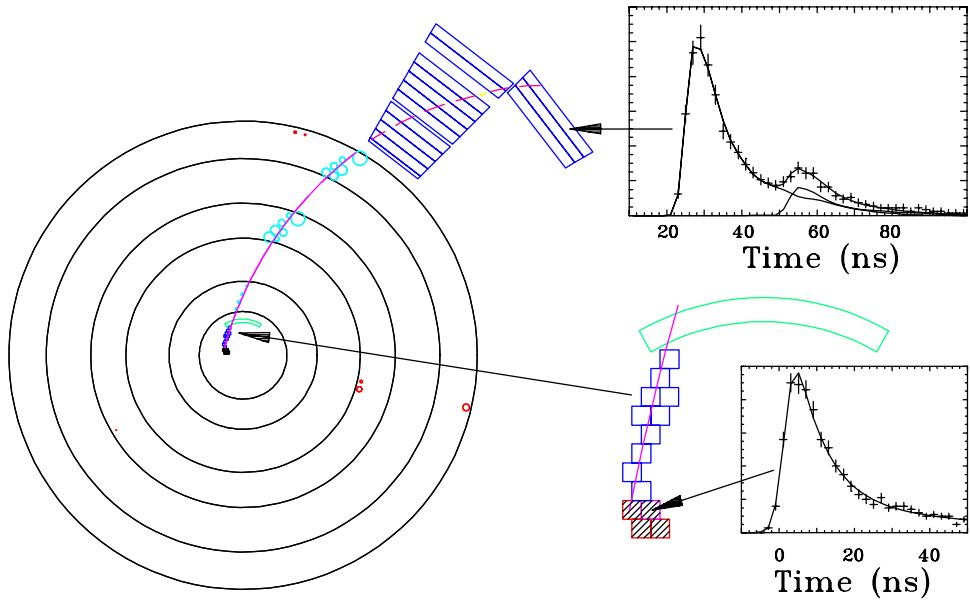
1995–97 Data



Monte Carlo



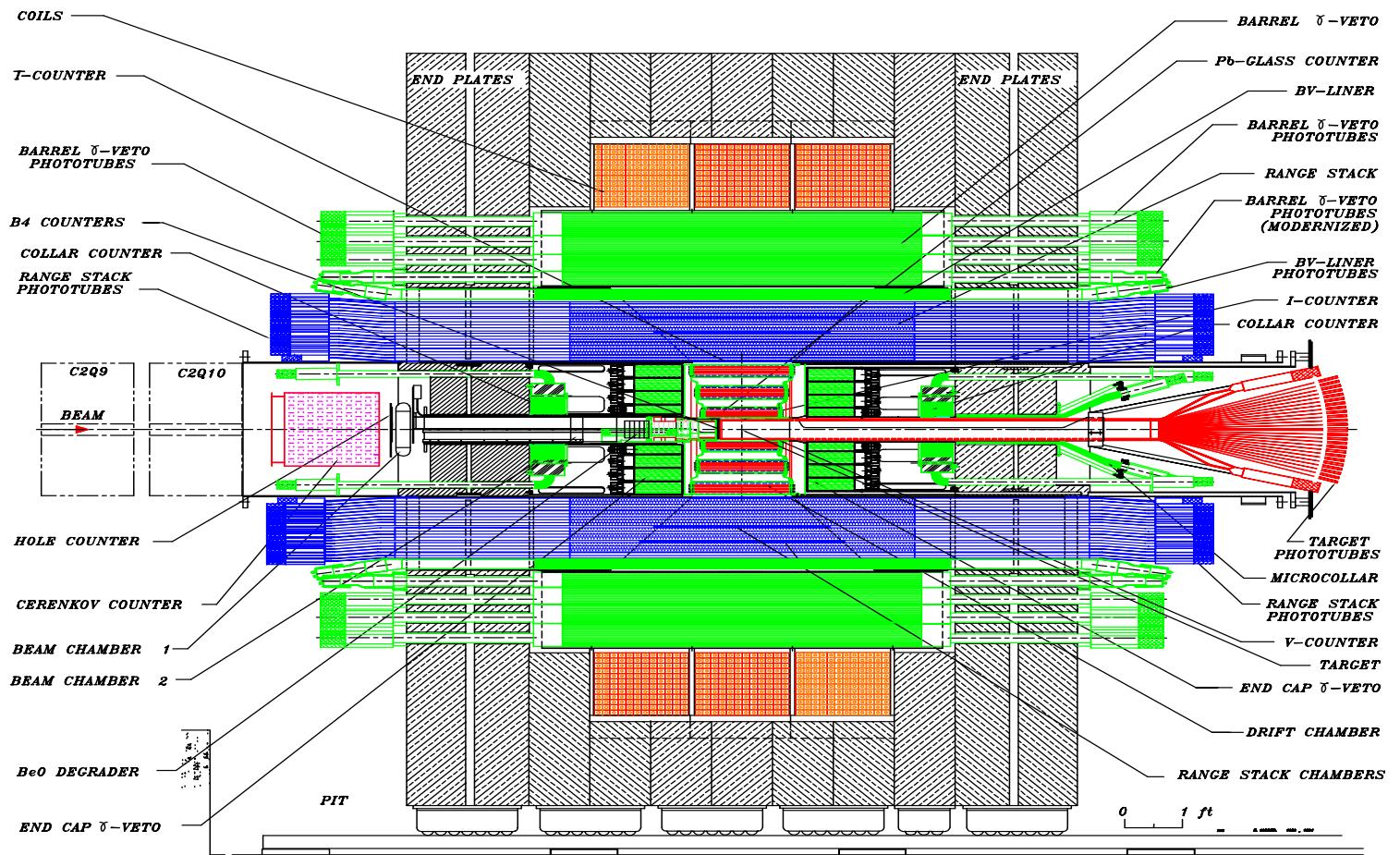
Event Display



$$\text{BR}(K^+ \rightarrow \pi^+ \nu \bar{\nu}) = 1.5^{+3.5}_{-1.3} \times 10^{-10}$$

[1995: PRL **79**, 2204 (1997), 1995–7: PRL **84**, 3768 (2000)]

E949: $K^+ \rightarrow \pi^+ \nu\bar{\nu}$



**Alberta/BNL/FNAL/Fukui/IHEP/INR/KEK
Kyoto/UNM/Osaka/TRIUMF/Yeshiva**

Sensitivity Improvement compared to E787 (1995):

- Increased spill length ($\times 1.56$)
- Lower Momentum ($\times 1.38$)
- Increased efficiency (trigger,DAQ,analysis) ($\times 3.2$)
 - Increase acceptance below $K_{\pi 2}$ peak [$\times 2$]
 - Re-optimize analysis for higher rates [$\times 2$]
- Total gain of $\times 14$ (per hour of running)

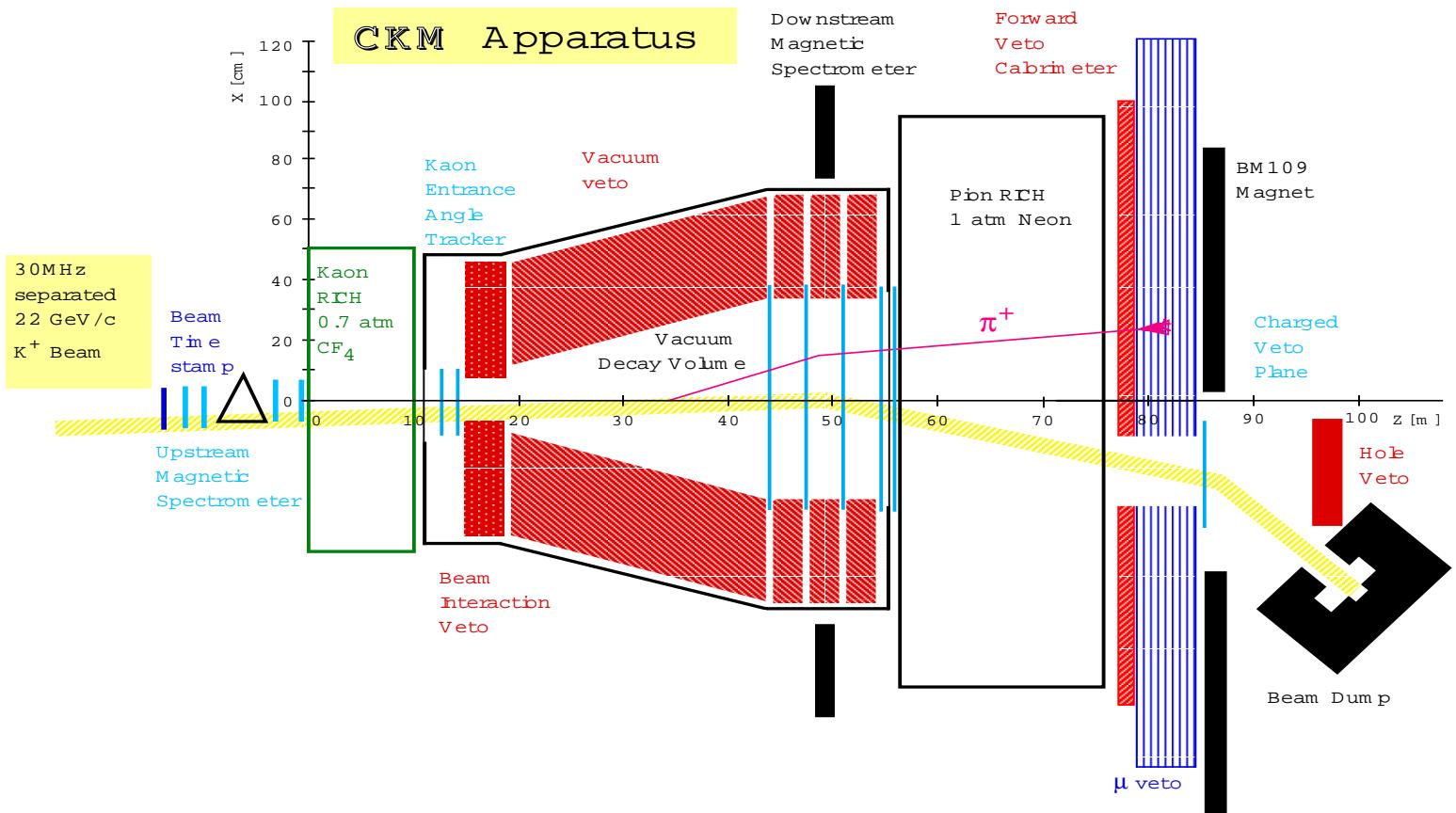
E949 Prospects

- Solid projection of sensitivity gain from E787
- Sensitivity for $B(K^+ \rightarrow \pi^+ \nu\bar{\nu})$ of $9\text{--}16 \times 10^{-12}$, an order of magnitude below the SM → observe 6-11 SM events.
- Background small and well understood.
- Background $\sim 10\%$ of SM signal. Benefit from extensive E787 measurements.

Status

- Approved and funded.
- Construction underway.
- Run during FY01–03 RHIC runs.

CKM (FNAL E905): $K^+ \rightarrow \pi^+ \nu \bar{\nu}$

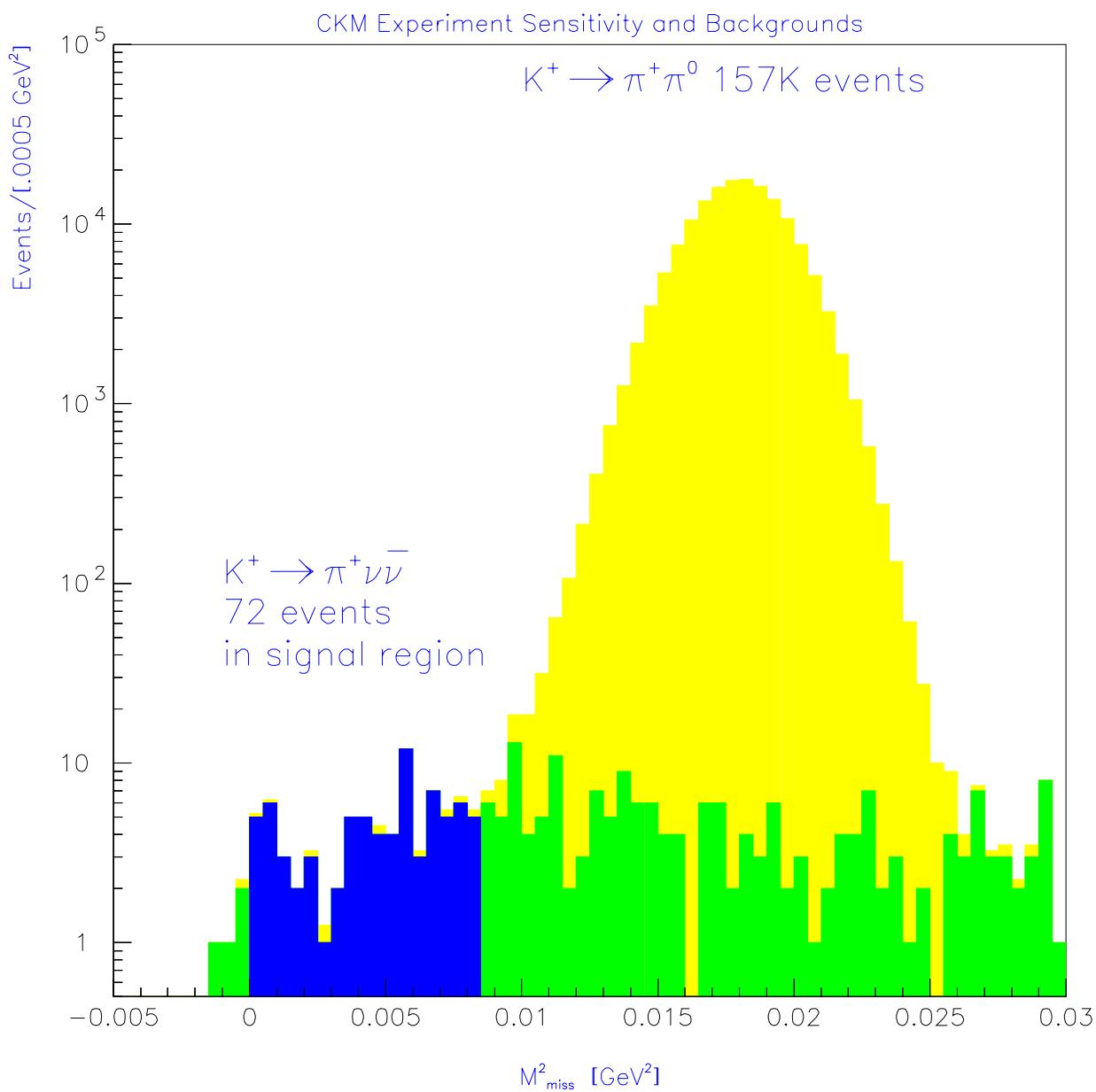


BNL/FNAL/IHEP/Michigan/Texas/UASLP/Virginia

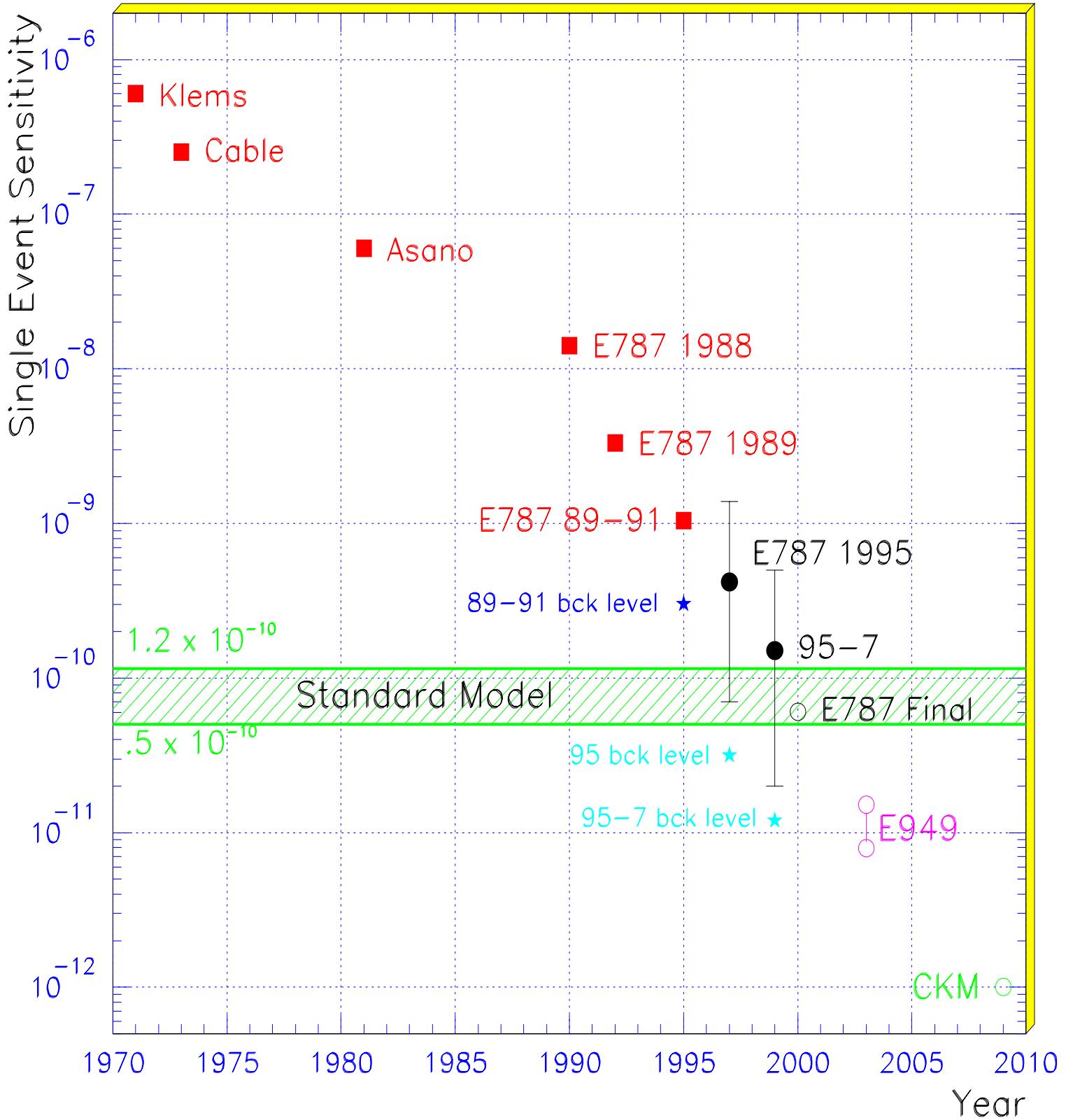
- Goal: $\sim 100 K^+ \rightarrow \pi^+ \nu \bar{\nu}$ events and determine $|V_{td}|$ to $\sim 7\%$.
- Decay in flight with a separated 22 Gev/c K^+ beam ($K/\pi = 2:1$).
- Redundant kinematics: velocity (RHIC's) and momentum (straws in vacuum) spectrometers.
- Hermetic photon veto, good μ -rejection.

CKM (FNAL E905): $K^+ \rightarrow \pi^+ \nu \bar{\nu}$

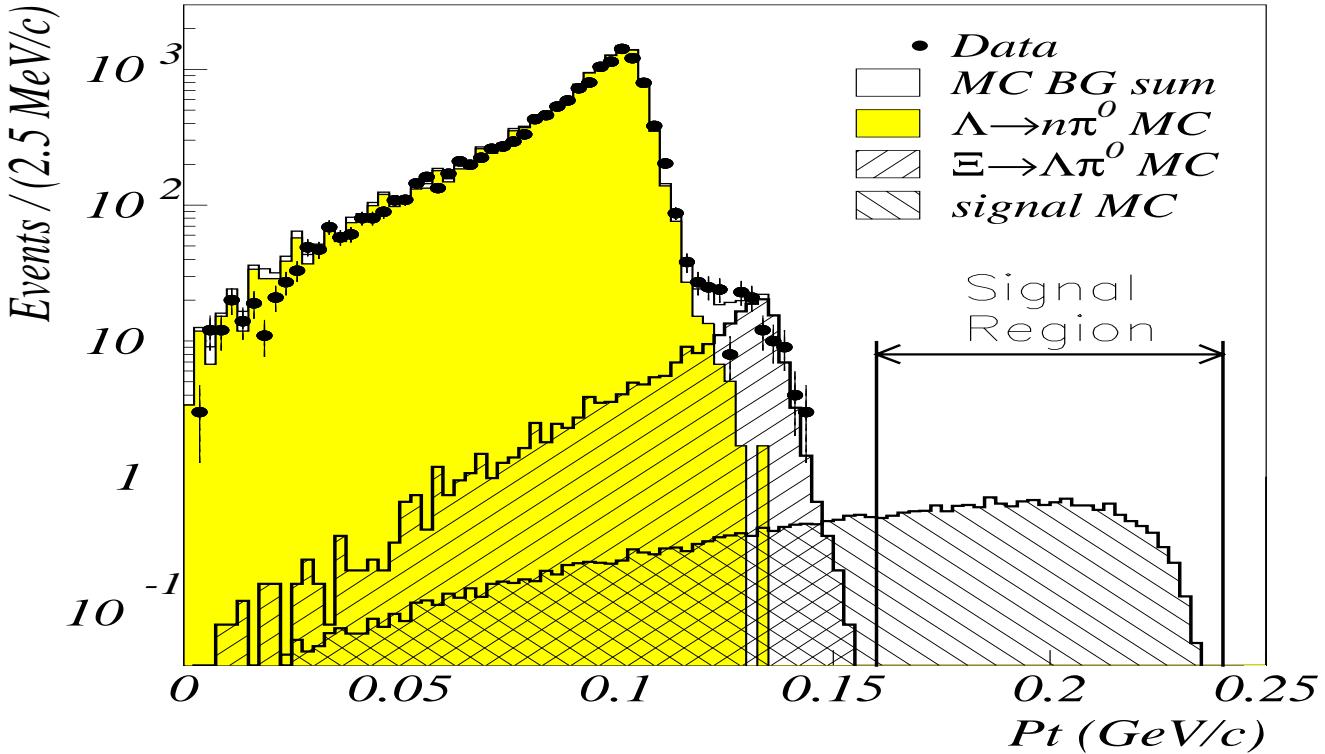
- Approved R&D project (11/11/98).
- Collect ~ 100 events in two years by ~ 2008
- Determine $|V_{td}|$ to $\sim 7\%$.



History of the Search for $K^+ \rightarrow \pi^+ \nu\bar{\nu}$



KTeV (FNAL E799): $K_L^\circ \rightarrow \pi^\circ \nu\bar{\nu}$



- Reconstruct $\pi^\circ \rightarrow ee\gamma$ vertex in beam.
- Select high P_T π° 's.
- Veto any additional activity.
- $B(K_L^\circ \rightarrow \pi^\circ \nu\bar{\nu}) < 5.9 \times 10^{-7}$ (90% CL) (PRD61, 072006, 2000).
- $B(K_L^\circ \rightarrow \pi^\circ \nu\bar{\nu})(\pi^\circ \rightarrow \gamma\gamma) < 1.6 \times 10^{-6}$ (90% CL) (PLB447, 240, 1999).

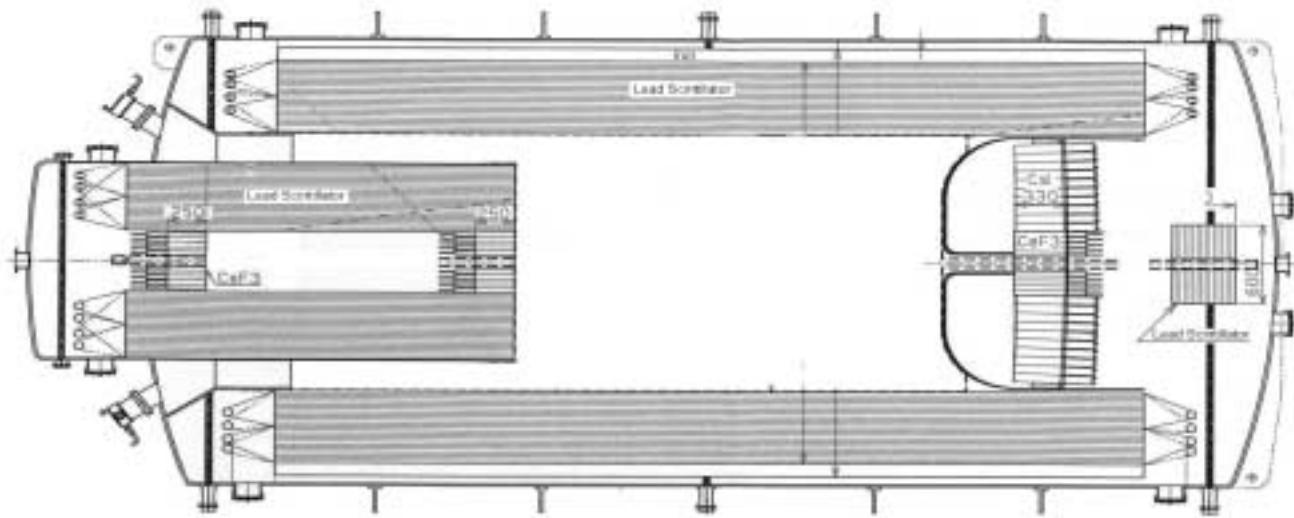
Best limit is indirect, from $B(K^+ \rightarrow \pi^+ \nu\bar{\nu})$:

$$\begin{aligned}
 B(K_L^\circ \rightarrow \pi^\circ \nu\bar{\nu}) &< r \times \frac{\tau_{K_L}}{\tau_{K^+}} \times B(K^+ \rightarrow \pi^+ \nu\bar{\nu}) \\
 &< 2.6 \times 10^{-9} \text{ (90% CL)}
 \end{aligned}$$

(PLB398, 163, 1997; PRL84, 3768, 2000)

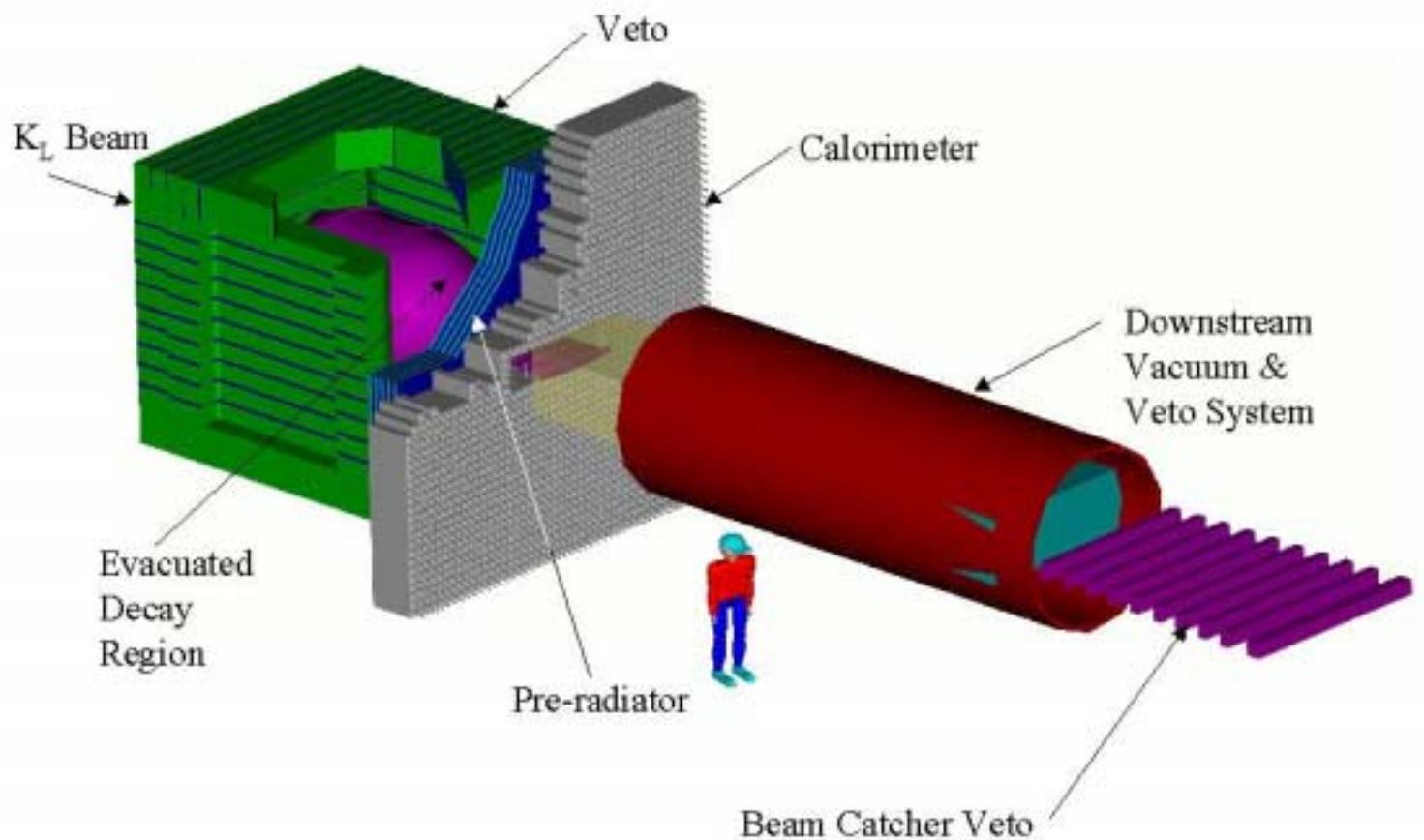
KEK E391: $K_L^0 \rightarrow \pi^0 \nu \bar{\nu}$

E391A DETECTOR PLAN



KEK/Osaka/Saga/Yamagata

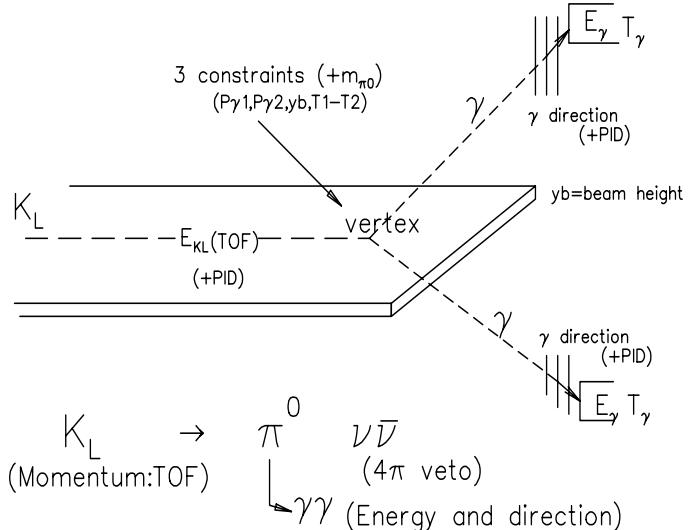
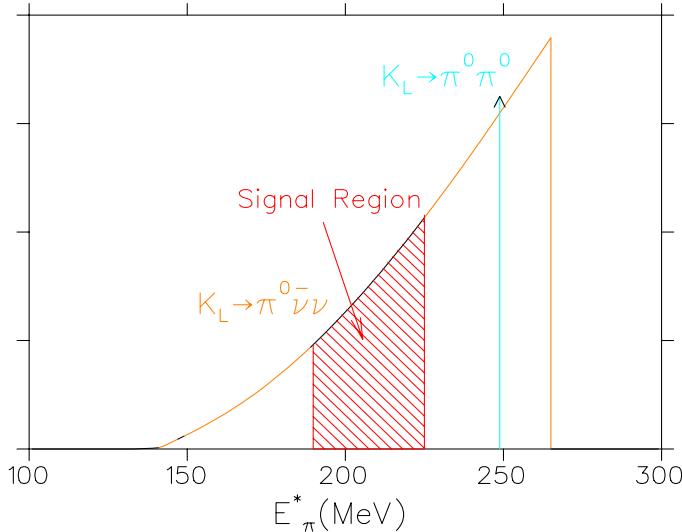
- Goal of E391a @ KEK-PS is to reach 10^{-10}
- Pencil beam. CeF_3/CsI calorimeter. Hermetic photon veto. Everything in vacuum.
- Learn more about backgrounds and techniques. Explore/rule out large enhancements BSM.
- E391 then will move to JHF and measure 100–1000 $K_L^0 \rightarrow \pi^0 \nu \bar{\nu}$ events
- Construction of E391a is underway, with beam coming soon.

KOPIO

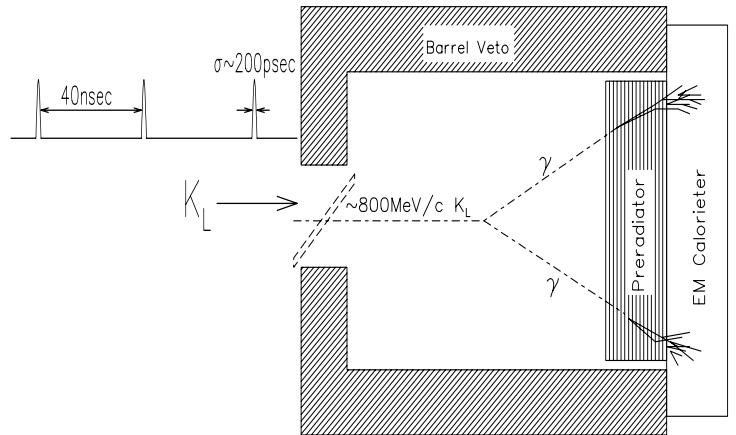
UBC/BNL/Cincinnati/INR/Kyoto/UNM
TJNAF/TRIUMF/VPI/Yale/Zurich

- Goal:
 - Measure BR to $\sim 15\%$ $\rightarrow \Delta\eta \sim 7\text{--}8\%$
- Sensitivity & Backgrounds
 - ~ 65 events/9000 hr ($\text{BR} = 3 \times 10^{-11}$)
 - Background 30 events (mainly $K_L^0 \rightarrow \pi^0 \pi^0$).

KOPIO Principles and Technique



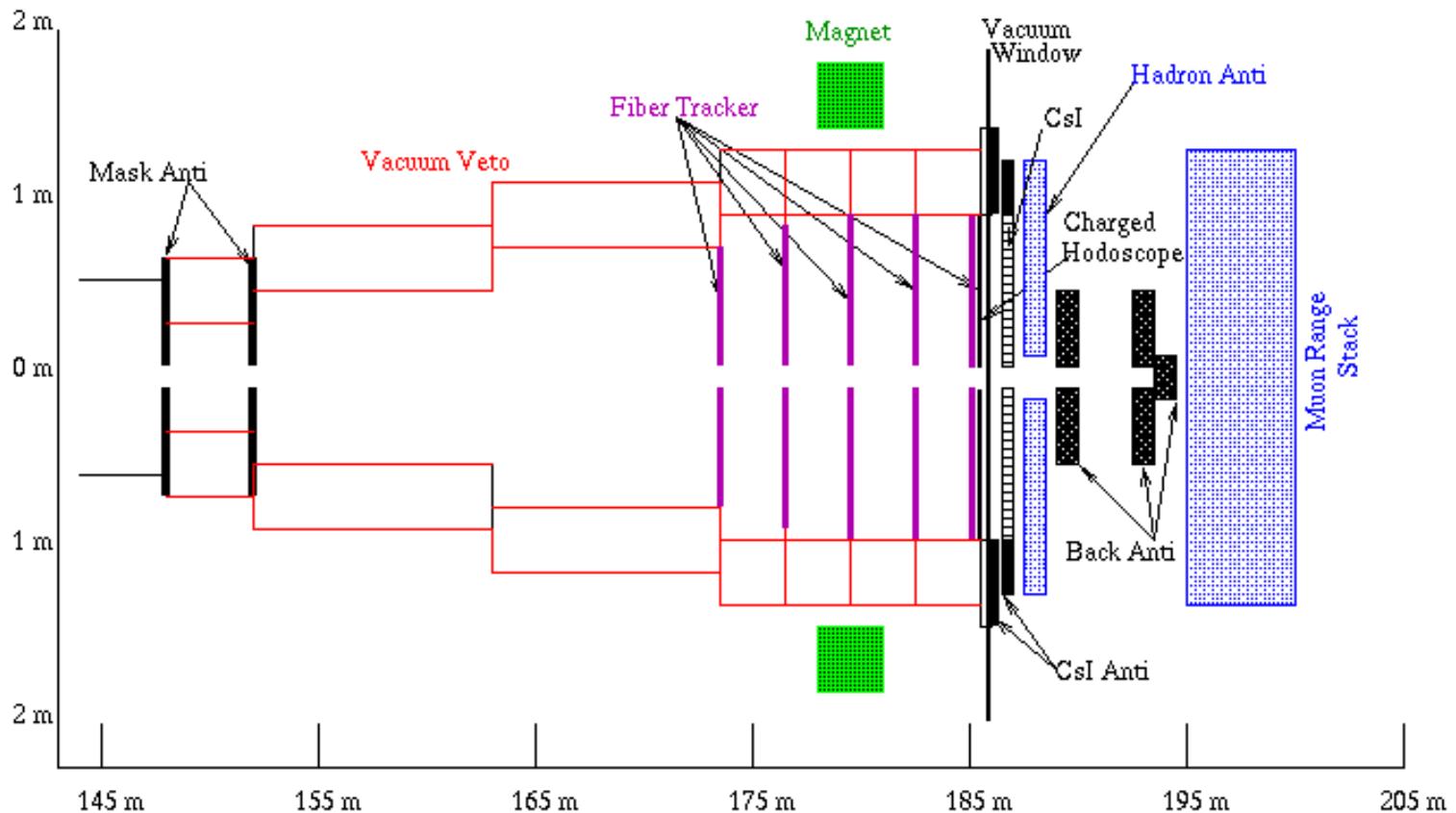
- Measure all initial & final state quantities.
 - Work in the K_L center of mass:
Bunched, large angle (low \vec{p}) beam.
 - Preradiator to measure γ directions.
 - Calorimeter for energies and times.
- Measure backgrounds.
- Hermetic photon veto ('beam catcher').



- Bunched beam
 - kinematically reduce $K_L^0 \rightarrow \pi^+ \pi^-$ by ~ 40 , most neutrons and accidental K^0 out of time, measure π^0 momentum spectrum (consistent with $K_L^0 \rightarrow \pi^0 \nu\bar{\nu}$).
- Low momentum beam
 - neutrons below π^0 threshold, no hyperons, neutrons and photons out of time.
- Determine decay vertex
 - 4C fit to π^0 , decay vertex in plane, reduce accidentals.

KAMI (FNAL E804): $K_L^\circ \rightarrow \pi^\circ \nu\bar{\nu}$

KAMI DETECTOR LAYOUT



Arizona/UCLA/Campinas/Chicago/Colorado
Elmhurst/FNAL/Osaka/Rice/Virginia/Wisconsin

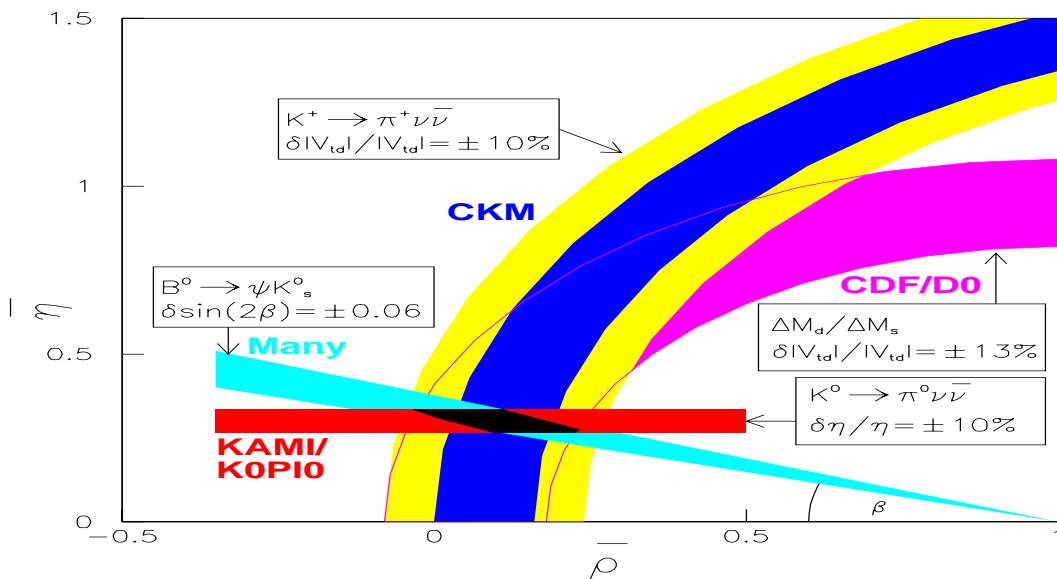
- Reuse KTeV CsI: precise $\pi^\circ \rightarrow \gamma\gamma$ reconstruction.
- Increased Photon Veto coverage
- Vacuum Fiber Tracker
- Single narrow beam
- Approved R&D project (11/11/98)
- KTeV run until 1/2000 (KAMI tests at end).
- Goal: collect ~ 100 $K_L^\circ \rightarrow \pi^\circ \nu\bar{\nu}$ events in $\sim 2\text{--}3$ years (2008?).

Future Kaon contribution to the CKM Matrix

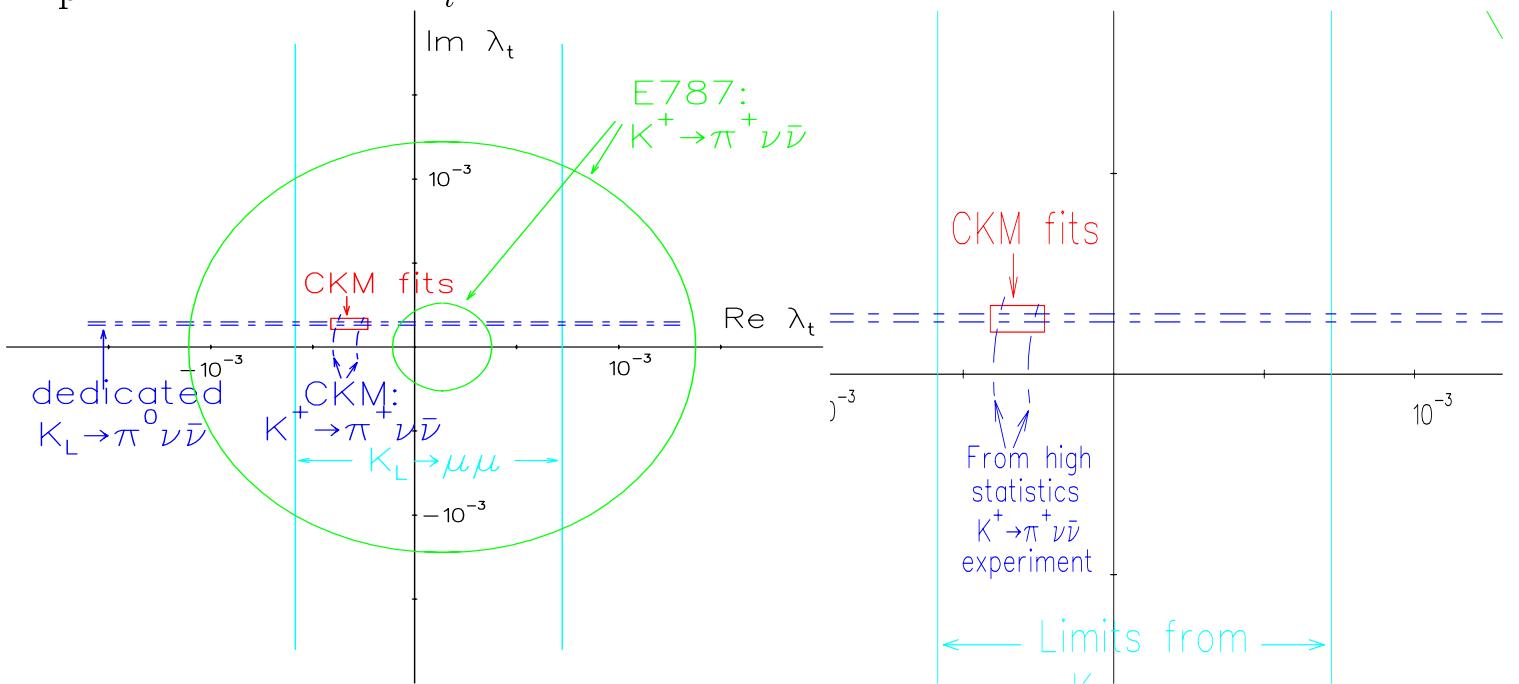
Measurements and tests of the Standard Model:

- Determine $Im(\lambda_t)$ and J_{CP} to 7–8% (now 22% and $\sim 40\%$)
- Overconstrain the angle β from $B_d^0 \rightarrow \psi K_S^0$ and $K_L^0 \rightarrow \pi^0 \nu \bar{\nu} / K^+ \rightarrow \pi^+ \nu \bar{\nu}$
- Overconstrain $|V_{td}|$ from $\Delta M_{B_s}/\Delta M_{B_d}$ and $K^+ \rightarrow \pi^+ \nu \bar{\nu}$

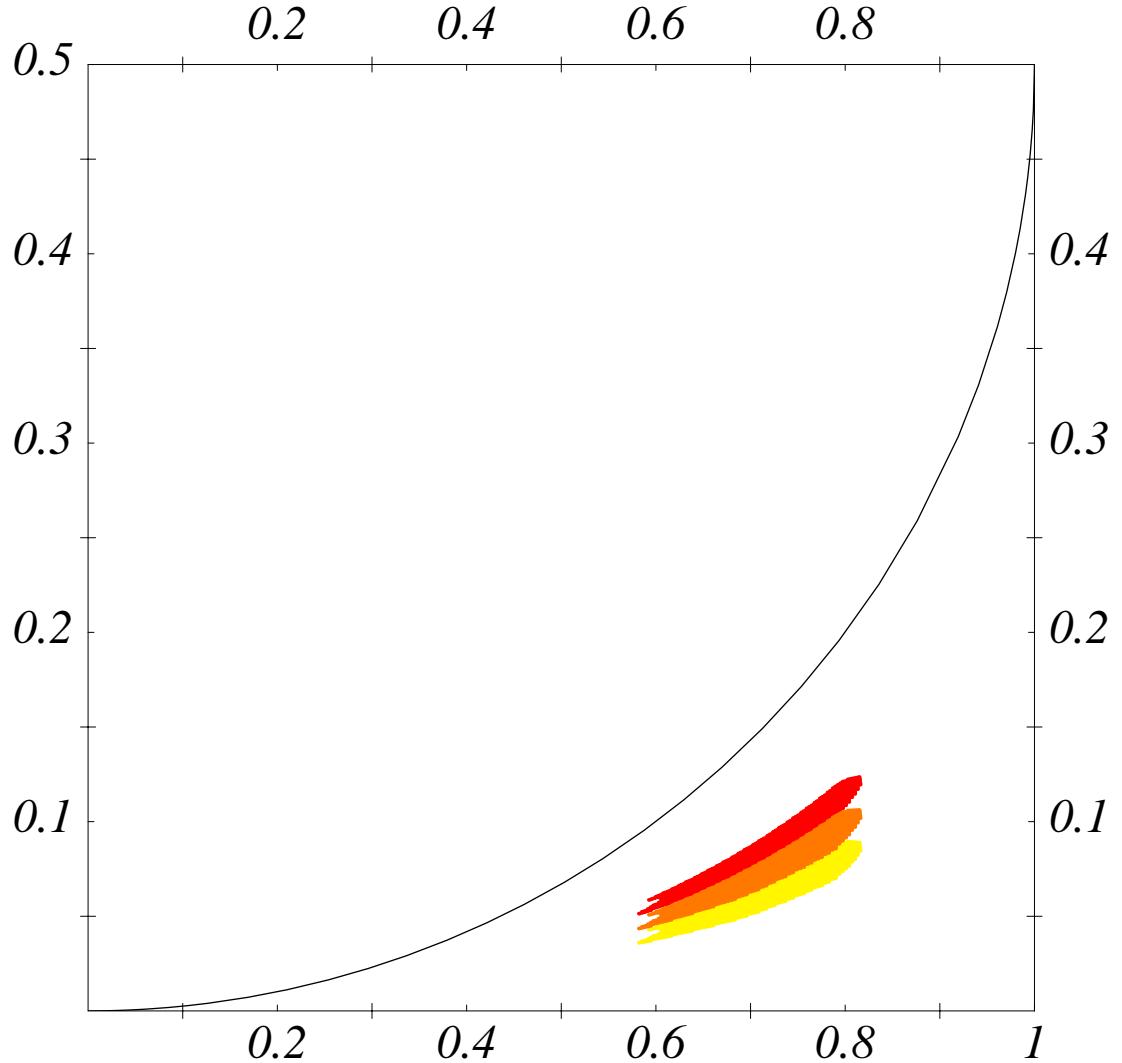
Future constraints on $\bar{\rho}$ and $\bar{\eta}$



Expressed in terms of λ_t :



$a_{\pi\nu\bar{\nu}}$



$\sin 2\beta$

FIG. 3. Relation between $a_{\pi\nu\bar{\nu}}$ and $\sin 2\beta$: The solid curves displays $a_{\pi\nu\bar{\nu}}(\sin 2\beta)$ for $\Delta = 0$. Only in this case there is a one-to-one correspondence between $a_{\pi\nu\bar{\nu}}$ and $\sin 2\beta$. A scan over the presently allowed region for $(\bar{\rho}, \bar{\eta})$ (c.f. Fig. 1) with $\Delta = 0.41$ ($\Delta_{max} = 0.56$, $\Delta_{min} = 0.29c$) yields the orange (yellow, red) region in the $\sin 2\beta - a_{\pi\nu\bar{\nu}}$ plane.

Conclusions

Lepton Flavor Violation

- Many extensions to the SM have been ruled out.
- Expect improvements in $K_L^0 \rightarrow \pi^0 \mu e$ from KTeV
- Future effort shifting to μ -decay

Other rare kaon decays

- Many new measures of semi-rare kaon decays ($\text{BR} > 10^{-9}$).
- Important tests of ChPT ($K_S^0 \rightarrow \gamma\gamma$, $K_L^0 \rightarrow \pi^0 \gamma\gamma$, ...).
- Useful for interpreting $K_L^0 \rightarrow \mu^+ \mu^-$ and $K_L^0 \rightarrow \pi^0 e^+ e^-$ ($K_L^0 \rightarrow \mu^+ \mu^- e^+ e^-$, $K_L^0 \rightarrow e^+ e^- \gamma$, $K_S^0 \rightarrow \pi^0 \gamma\gamma$, ...).

Measurements of CKM matrix

- Interesting new results on $K_L^0 \rightarrow \mu^+ \mu^-$ and $K^+ \rightarrow \pi^+ \nu\bar{\nu}$.
- Future prospects for $K^+ \rightarrow \pi^+ \nu\bar{\nu}$ and $K_L^0 \rightarrow \pi^0 \nu\bar{\nu}$ are bright.
- Expect many new results in the B system soon.
- Anticipate important tests of SM picture of quark mixing and CP-violation from comparison of B's and K's.

Relevant Radiative Kaon Decay Results

There are several new measurements of $K_L \rightarrow \gamma^* \gamma$ and $K_L \rightarrow \gamma^* \gamma^*$. These may be used to estimate the long distance dispersive contribution to $K_L^\circ \rightarrow \mu^+ \mu^-$ (D'Ambrosio, Isidori and Portales PL **B423**, 385). Although there is some controversy on this topic (Valencia NP **B517**, 339).

- $K_L^\circ \rightarrow e^+ e^- \gamma$ $BR = (1.06 \pm .02 \pm .02 \pm .04) \times 10^{-5}$ NA48 [PLB**458**(99)553]
 $\alpha_K^* = -0.36 \pm 0.06 \pm 0.02$ (100k events KTeV-1997)
- $K_L^\circ \rightarrow \mu^+ \mu^- \gamma$ $BR = ((3.23 \pm 0.23 \pm 0.19) \times 10^{-7}$ E799 [PRL**74**(95)3323]
 $\alpha_K^* = -0.028^{+0.115}_{-0.111}$ (6700 events KTeV-1997)
- $K_L^\circ \rightarrow e^+ e^- e^+ e^-$ $BR = (4.14 \pm 0.27 \pm 0.31) \times 10^{-8}$ KTeV [ICHEP98]
- $K_L^\circ \rightarrow e^+ e^- \mu^+ \mu^-$ ~ 40 events KTeV [DPF99]